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# Recent advances in plant protein-based sustainable packaging films: resource, applications, challenges and future directions

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This review discussed the plant protein in sustainable food packing film/coating from perspective of innovative protein sources, adequate additives, sustainability, and innovative fabrication technology. The incorporation of biopolymers (plasticizers, polysaccharides and lipids) on the properties and its application was investigated. These biopolymers realized the complementarity between protein and biopolymers within films. Further, this review explores the link between protein-based packaging materials and innovative technologies like electrospinning, solution casting, and dry extrusion. The study investigates how these biopolymers complement proteins to enhance the material's barrier and mechanical properties, thereby improving food preservation and shelf life. Finally, the review evaluates the sustainability of these materials and their application in food preservation, providing a foundation for future exploration of innovative plant proteins in this field.

## KEYWORDS

application, fabrication technology, food packaging, plant protein, sustainability

## 1 Introduction

Food packaging film/coating is a kind of packaging material wrapped around the surface of food, which is used to protect and preserve the foodstuff. Nowadays, most of traditional food packaging films are synthetic plastics made from fossil fuels (Jafarzadeh et al., 2021). Plastics packaging not only take years to degrade but also release toxic chemicals and odors during the packaging process, bringing great pressure to environmental governance and food safety concerns (Alirezalu et al., 2021; Madanayake et al., 2021). To address the environmental impact of conventional plastics, recent research has focused on biodegradable polysaccharides, lipids, and proteins as alternatives to plastic packaging. Among these, plant proteins have gained interest due to their favorable properties for film packaging, including processability, reduced food contamination, biocompatibility, biodegradability, and the integrity of structure–property–performance relationships (Nasrabadi et al., 2021; Sá et al., 2020).

In recent years, plant proteins such as zein, soybean isolate protein (SPI), and wheat gluten protein (WGP) have been increasingly used to create edible films with desirable properties. These proteins possessed strong film-forming capacity through self-assembly, and their characteristics including conformation, surface hydrophobicity, and thermal stability were crucial for film formation (Banerjee et al., 2021; Kumar et al., 2022b). However,

food-packaging materials must keep their integrity and protect products from heat changes throughout storage, processing, and transportation; thus, mechanical strength, extensibility and thermal stability are critical (Bahrami et al., 2022). Generally, edible films made from a single plant protein have certain limitations, such as low mechanical strength, poor moisture and antimicrobial. To address these issues, plant-based protein films are typically enhanced by incorporating two or more bio-macromolecular polymers, fabricating film with porous network structure by the interaction between different molecules (Otoni et al., 2017). This approach greatly improved the film's performance by allowing the properties of different materials to complement each other, allowing for tailored ways for various food packaging needs.

The review overviewed recent progress on plant protein-based films and coating. The flow diagram was shown in Figure 1. Firstly, the plant-derived protein sources explored for food packaging was discussed. Next, we focused on the impact of biopolymers additives (e.g., plasticizers, polysaccharides and lipids) on the properties and functionality of the plant protein-based film. We also introduced the fabrication technique used for plant protein-based films. Finally, we summarized their application in food preservation and gave an outlook on its future development prospect.

## 2 Plant-based protein as materials used for food packing

Plant-based proteins, obtained from various natural sources, have vital roles in edible packing development due to their film-forming capacity, excellent barrier properties (such as gas, moisture and UV barrier) and biological activities. Among which, several protein sources have been explored for potential use as packaging materials (Table 1).

### 2.1 Zein

Zein, with unique amino acid profile and its disulfide bonds enables it have excellent film forming, allows its extensive use in food preservation (Mouzakitis et al., 2022). While previous studies have successfully fabricated pure zein films and coatings, the nanofibers were found to have poor mechanical properties, such as brittleness and limited flexibility, which restrict their application and hinder their practical value. Incorporating biopolymers and employing advanced fabrication techniques like hybrid electrospinning has been considered as a feasible approach to solve these problems. For instance, Zhou and

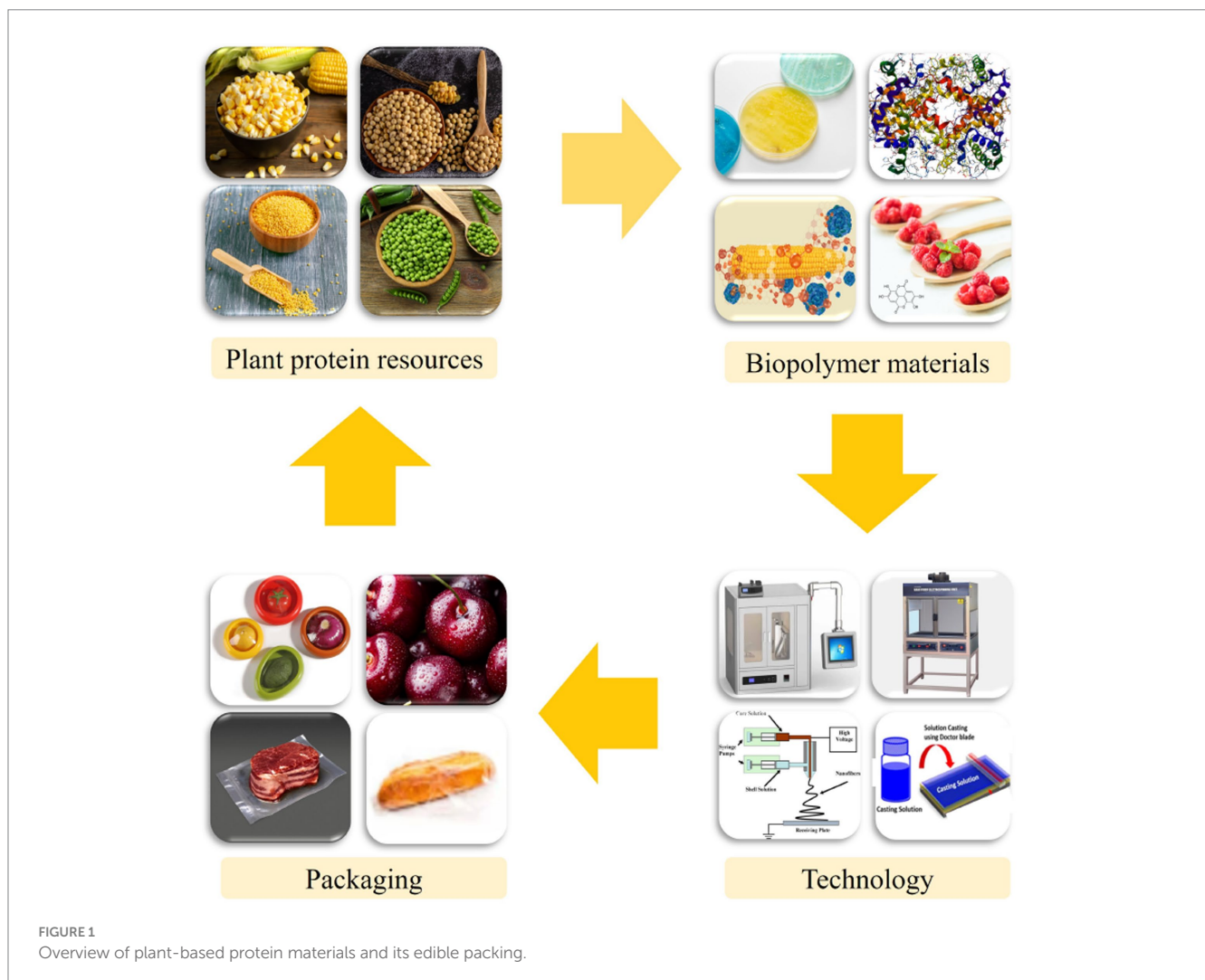


FIGURE 1 Overview of plant-based protein materials and its edible packing.

TABLE 1 The formulations, attainment methods, and properties of plant protein-based packaging.

Plant protein	Methods	Film-forming components	Characteristics	References
Zein	1. Solution casting 2. Extrusion molding 3. Electrostatic spinning and spraying	1. Chitosan nanoparticles, pomegranate peel extract 2. Glycerol, essential oils eugenol (EUG), carvacrol (CAR), and thymol (THY)	1. High transparency 2. Moisture resistance 3. Oxygen barrier 4. Heat resistance 5. Brittleness, easy breakage and poor flexibility	Cui et al. (2020), Boyaci et al. (2019)
Soy isolate protein	1. Heating 2. Extruding 3. Spinning 4. Casting 5. Thermally compacting	1. Glycerol, Pinhão extract (Catechin) 2. Glycerol, mango kernel extracts 3. Glycerol, cellulose nanocrystals (CNCs)	1. Low lipid, oxygen, and carbon dioxide permeability 2. High transparency 3. Low mechanical strength 4. Poor moisture and antimicrobial resistance	Chen et al. (2019), Li F. et al. (2019), Li J. M. et al. (2019), Adilah et al. (2018)
Wheat gluten protein	1. Solvent casting 2. Compression 3. Molding 4. Extrusion 5. Electrospinning	1. Glycerol, various natural biocides (carvacrol and cinnamaldehyde) 2. Glycerol, cellulose nanofibers (0–10 wt %)	1. Low oxygen permeability 2. Flexibility and firmness 3. Limited water vapor resistance 4. Low mechanical strength and poor transparency	Chen X. et al. (2022), Chen Y. et al. (2022), Gómez-Heincke et al. (2016), Bagheri et al. (2019)
Peanut protein	1. Solvent casting 2. Surface film formation	1. Potato starch, chitosan 2. Citric acid, glycerol 3. Pea starch (PS), glycerol	1. Anti-emulsification 2. Film-forming capacity 3. Antioxidant activity 4. Hydrophilicity and poor mechanical properties	Zhong et al. (2017), Meng et al. (2020), Sun et al. (2013)
Cottonseed protein	1. Solvent casting 2. Hot pressing	1. Poly (vinyl alcohol) (PVA), triethanolamine (TEA) 2. Carboxymethyl cellulose (CMC), glycerol	1. Antioxidant and antimicrobial actives 2. High emulsifying abilities 3. Oil/water absorption capacity 4. Surface hydrophobicity	Chen et al. (2019), Cheng H. N. et al. (2024) and Cheng J. et al. (2024)
Millet prolamin	1. Solvent casting 2. Electrospinning 3. Compression, molding and extruding	1. Zein, acetic acid 2. Glycerol, citric acid	1. Physicochemical stability 2. Good hydrophobicity 3. Film-forming capacity 4. Thermal stability 5. Antioxidant properties	Chen X. et al. (2022), Chen Y. et al. (2022), Al-Hashimi et al. (2020), Wang H. D. et al. (2024), Wang S. M. et al. (2024), Sachdev et al. (2023)

Wang (2021) enhanced zein-methylcellulose composite films by adding oleic acid and polyethylene glycol, results reveal that polyethylene glycol significantly improved film's elongation. Another study has been conducted by Mouzakitis et al. (2022) that zein-based coatings with sunflower oil can reduce crumbliness and effectively extend the shelf life of wheat bread. Wei et al. (2024) prepared plasticized zein films using various deep eutectic solvents (DESs), and investigated the plasticization mechanism of DESs, this result found that DESs could significantly improve the morphology, mechanical properties, water resistance, and antibacterial activity of zein films. Moreover, the application of these films as a coating on mangoes effectively reduced the weight loss rate, and delayed the decreases in peel brightness, firmness, and soluble solid content. Recent studies have also focused on incorporating active nanomaterials. Liu et al. (2023) fabricated eugenol/caffeic acid-mesoporous silica nanoparticles/zein (EG/CA-MSN/Zein) composite films via a casting method. The incorporation of EG/CA-MSN significantly improved barrier and mechanical properties of the composite films. Specifically, when the addition amount of EG/CA-MSN was 9%, the composite film exhibited the lowest water vapor transmission rate, achieved a

tensile strength of 18.86 MPa, which was significantly superior to that of the pure zein film. While zein-based films/coatings show promise for food preservation, most of them remains at the laboratory level and have not yet to achieve larger-scale industry application. Moreover, the impact of various factors on the coating's effect on food safety requires thorough evaluation.

## 2.2 Soy protein isolate (SPI)

SPI is widely available as a by-product from industries like food processing and animal feed production. It consists of various globulin fractions (2S, 7S, 11S, and 15S) with numerous hydrogen, hydrophobic, and ionic bonds, and the cross-linking between protein molecules is relatively strong (Liu R. et al., 2017; Liu X. R. et al., 2017), so its film-forming properties are excellent. The film-forming ability together with its low cost makes SPI became attractive candidates for food packaging applications. SPI films also provide superior barrier properties against oxygen and carbon dioxide. Studies showed that SPI films significantly reduced oxygen permeability (OP) values compared

to polysaccharide-based films, such as those made from cellulose, starch, and pectin (Koshy et al., 2015). Although SPI films have shown some effectiveness in food packaging, especially for oxidation-sensitive products, SPI films suffered from low mechanical strength, poor moisture resistance, and susceptibility to bacterial growth (Li F. et al., 2019; Li J. M. et al., 2019). To enhance SPI film's properties, nanoparticle modifications, particularly with ZnO nanoparticles was employed for improving barrier, mechanical, and antifungal qualities. Other nanoparticles like nanocellulose, nano-SiO<sub>2</sub>, and nano-TiO<sub>2</sub> have also been explored for SPI films (Tang et al., 2019; Liu et al., 2019; Xu et al., 2019). For instance, researchers blended ZnO NPs with SPI-based film by the solution casting method and discovered that ZnO NPs enhanced the films' tensile strength and elongation at break, thereby improving their strength and flexibility. In spite of having conducted the nanoparticle modification and reinforcements for SPI film, they still lack satisfactory antimicrobial properties in practical applications. Further research is required to investigate the antimicrobial effect of nanoparticles in SPI films to ensure their successful application in packaging.

### 2.3 Wheat gluten protein (WGP)

Wheat gluten protein (WGP), as a high-quality cereal protein, account for 80–85% of the total wheat protein, and it is primarily composed of glutenin and gliadin, which impart cohesiveness and elasticity properties. WGP displays excellent film-forming properties based on its viscoelasticity, as well as an efficient oxygen gas barrier which can slow down the rate of lipids oxidation. The WGP film was found to show a low oxygen permeability (OP) value when compared to other biopolymer and polymer materials (starch, chitosan, polyethylene terephthalate (PET), polylactic acid (PLA), and hemicellulose) (Chen X. et al., 2022; Chen Y. et al., 2022). While WGP films have limited water vapor resistance and mechanical strength, these properties can be enhanced through cross-linking modification methods. Nataraj et al. (2018) fabricated WGP films reinforced with banana fibers using solution casting and compression molding, results discovered that this cross-linking could reduce the water absorption of the films from 500% to approximately 200%, and the strength of the films increased substantially from 3.5 MPa to 13 MPa. Although WGP has been employed in food products and edible films, its consumption may cause issues for celiac disease populations, like diarrhea, weight loss, bloating, and anemia. More research is warranted to study their safe content limit in WGP based film.

### 2.4 Pea protein isolate (PPI)

Pea protein isolate (PPI), recognized as one of the most abundant and sustainable plant protein sources, is frequently utilized in the food industry due to its high yield, cost-effectiveness, accessibility, and minimal allergenicity (Lu et al., 2020; Lam et al., 2018). In the field of edible films, PPI demonstrated excellent film-forming ability and superior ultraviolet (UV) barrier properties. However, like many plant protein, its native application is often constrained by suboptimal mechanical performance and water resistance (Cheng et al., 2022; Ge et al., 2020). To overcome these inherent limitations and enhance functionality, recent research has focused on incorporating active

components into the PPI film matrix. For instance, Cheng H. N. et al. (2024) and Cheng J. et al. (2024) recently fabricated active PPI-based films by successfully incorporating oregano essential oil (OEO). The study demonstrated that the inclusion of OEO significantly tailored the physical properties of the films, notably improving mechanical performance, water resistance, color attributes, and thickness. In addition, the PPI-based film containing 2.0% OEO exhibited remarkable antibacterial efficacy, displaying significant inhibition against the growth of *Salmonella strains*. Furthermore, its practical application was confirmed: coating chicken breast with the optimized PPI-OEO film notably extended the product's shelf life, achieving a spoilage delay of 5 days through effective bacterial inhibition. This work exemplifies the recent research on developing high-performance, active, and sustainable PPI-based packaging solutions.

### 2.5 Other plant-based protein

New plant proteins sources are gradually being explored as food packing materials, and some proteins (such as peanut protein, cottonseed protein, and millet prolamin) are being developed as promising food packaging materials due to their proven hypoallergenic and other desirable characteristics such as biological and nutritional value. Peanut protein, derived from peanut meal, has a higher protein content and better functional attributes such as excellent anti-emulsification, film-forming capacity and antioxidant activity, making it a promising candidate for food packaging. Zhong et al. (2017) successfully developed an active film using modified peanut protein combined with thymol (TML), which exhibited low water vapor permeability (WVP) and strong antioxidant and antimicrobial activity. However, they suffer from significant hydrophilicity and poor mechanical properties.

Cottonseed protein, which constitutes 30–40% (w/w) of the cottonseed kernel, demonstrates favorable film-forming properties and various bioactivities such as antioxidant and antimicrobial, as well as high emulsifying capacity with excellent oil/water absorption and surface hydrophobicity (Kumar et al., 2022a). These properties indicated that cottonseed protein has potential applicability for food packaging. In a study, cottonseed meal protein (CSP) film incorporating nanoclay and carvacrol was prepared, results showed that this film exhibited high tensile strength and antimicrobial activity (Jo et al., 2012).

Millet prolamin, a protein derived from millet grains, constitutes approximately 60% of the total millet protein. It is similar in structure and properties to zein, contains a large number of hydrophobic amino acids, and is physiochemically stable and has good hydrophobicity, film-forming capacity, thermal stability as well as antioxidant properties (Chen X. et al., 2022; Chen Y. et al., 2022). This suggested that millet prolamin maybe a favorable potential protein resource for food packaging. Wang H. D. et al. (2024) and Wang S. M. et al. (2024) fabricated millet gliadin/zein composite nanofibers, and found that these nanofibers exhibited high mechanical strength and water resistance. However, there were still fewer research on new plant protein films, and only preliminary discussions on above three kinds of plant-based protein films were carried out, future investigations could further elucidate their functional properties and explore their potential in food packaging scope.

### 3 Plant protein-based composite films/coating

Single plant protein-based films may exhibit poor mechanical properties, weak water resistance, and lack of antimicrobial properties (Kong et al., 2025). The incorporation of modifiers and biopolymers into films to enhance these properties are exploring direction by researchers for food preservation (Figure 2).

#### 3.1 Protein/modifier

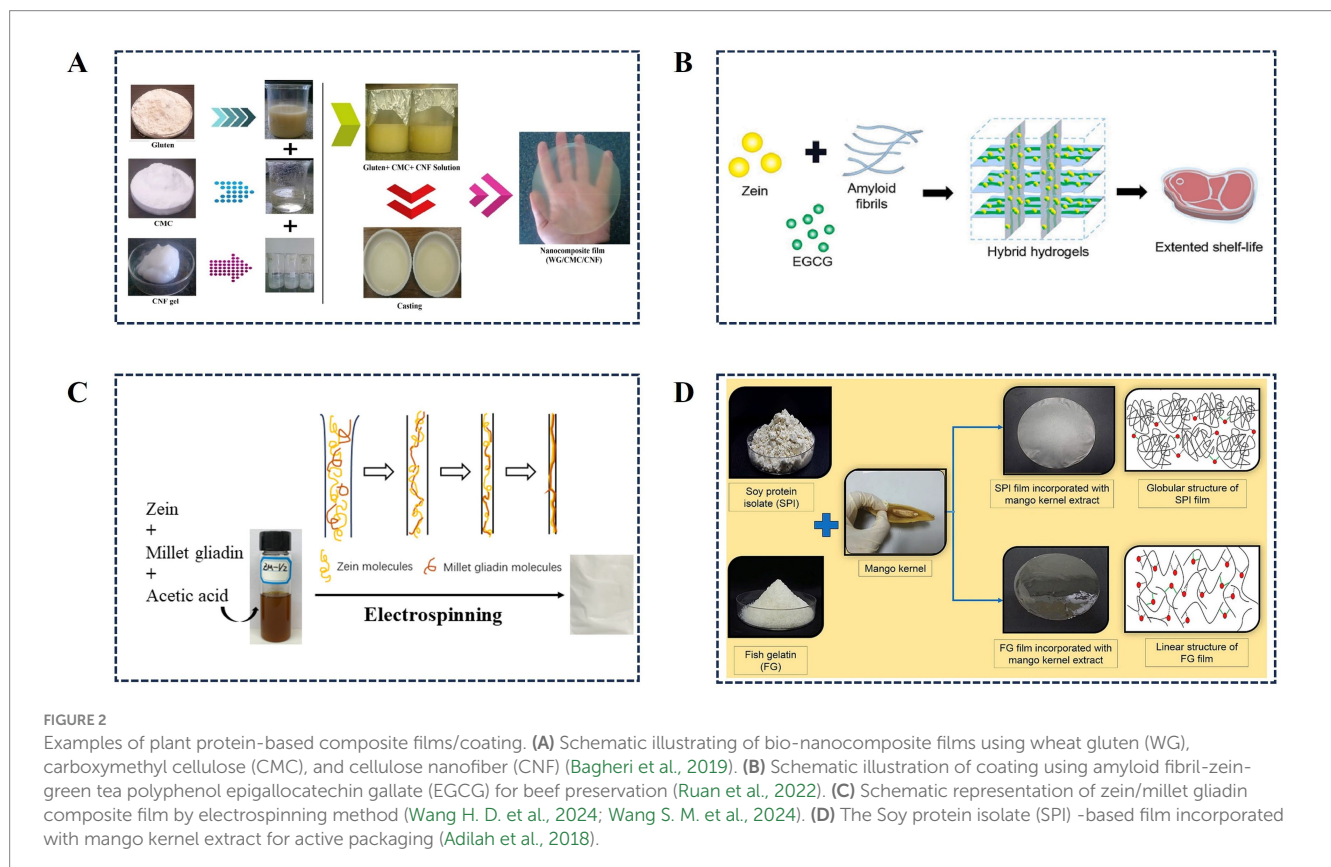
The most commonly used of modifiers are plasticizers, cross-linking agents and nanoparticles. Plasticizers are typically small organic polymers with high boiling points, which could promote protein molecules interactions in films, thereby enhance the opacity, mechanical strength, and barrier properties of plant protein-based films (Huo et al., 2018). Glycerol, the most often used plasticizer, was explored in zein and SPI-based films, and research results indicated that the film had high tensile strength (TS) and low water vapor permeability (WVP) (Hopkins et al., 2019). Nanoparticles, as a wide range of additives to plant protein-based films, have the advantages of high stability and antimicrobial activity and low volatility. They could improve the physical and chemical properties of films by interacting with plant proteins and forming a physical barrier. Guo et al. (2019) fabricated a nanocomposite film from SPI/polyvinyl alcohol and montmorillonite (MMT). It was found that this nanoparticle improved the mechanical properties, water sensitivity and thermal stability of film with increasing of MMT content. Mechanistically, MMT platelets

intercalate or exfoliate within the polymer matrix, increasing the rigidity and thus improved the TS. Additionally, the ZnO nanoparticle increased the tortuosity of SPI films and enhanced microbial inhibition and the TS by 16 and 231%, respectively, by hindering the diffusion of oxygen and thus reduces the oxygen permeability (Tang et al., 2019). The enhanced TS is primarily attributed to strong interfacial interactions (e.g., hydrogen bonding, electrostatic attraction) between the protein chains and the high-surface-area nanoparticles.

However, the use of plasticizers and nanoparticles to modify single plant-based protein films has limited benefits. For instance, nanoparticle modification tends to be expensive, complex, and challenging to process. Recent research suggests that combining polysaccharides, lipids, and proteins or integrating multiple polymers may enhance film's performance by addressing the shortcomings of individual modifiers.

#### 3.2 Protein/polysaccharides

Polysaccharides have water-soluble, biocompatibility and stable film-forming properties, while their moisture barrier and water resistance are poor due to hydrophilicity. The incorporation of polysaccharides into protein film could improve its barrier performance by increasing the molecular density and decreasing the permeability (Roy et al., 2024). Polysaccharides, due to their long-chain helical structures, enhance the thickening and gelling properties, thereby improving the film-forming capacity of proteins. Currently, effective polysaccharides used in packaging materials mainly include



cellulose derivatives, starches, chitosan, and gums. Cellulose nanofibers exhibit high mechanical resistance, excellent biocompatibility, and superior water retention capacity. Maroufi et al. (2023) fabricated composite films using soy protein isolate (SPI) and  $\kappa$ -carrageenan as the matrix, with bacterial cellulose nanofibrils (BCN) incorporated as a reinforcement. The incorporation of BCN, with increasing concentration, led to a significant enhancement in the film's physical and barrier properties, including increases in thickness, tensile strength (TS), and Young's modulus (YM), while simultaneously achieving a substantial reduction in water solubility, water content, and water vapor permeability (WVP). This highlights the effectiveness of nanocellulose in overcoming the inherent weaknesses of protein-polysaccharide blends. Meanwhile, starch is a vital component in the production of biodegradable biofilms due to its renewability, low cost, easy availability, good processability and inherent non-toxicity (Mehboob et al., 2020). However, its high-water sensitivity often requires chemical modification or blending for practical application. Ke et al. (2025) explored the interaction between short-chain fatty acid-modified starch and soy protein isolate (SPI). It was found that the synergistic effect of starch incorporation and SPI enables the composite film to form a dense and smooth surface structure, significantly reducing water vapor permeability (WVP). Furthermore, the increase in the chain length of acylated starch enhanced the film's ultraviolet (UV) absorption capacity, reduced light transmittance, and improved light barrier performance.

Chitosan, in particular, is favored for plant protein-based packaging films due to its high tensile strength (TS), antioxidant and antimicrobial properties, and thermal stability, which make it a popular choice for food anticorrosion and preservation material. Bueno et al. (2021) reported that films combining chitosan and zein offer excellent gas and water barrier properties. Gums are also one of the commonly used polysaccharides materials, Yang et al. (2015) explored using hsian-tsoo gum (HG) to enhance soy protein isolate (SPI) film properties, the results confirmed SPI and HG could form new bonds through Maillard interactions, yielding to high tensile strength (TS) and elongation at break (EAB) of film. This covalent cross-linking formed an irreversible and robust structure, significantly enhancing the mechanical properties and thermal stability. Furthermore, new sources of polysaccharides, such as the composite films made from pregelatinized starch and zein, demonstrated improved tensile properties and water resistance (Teklehaيمانot et al., 2020).

### 3.3 Protein/lipids

Lipids possess limited mechanical properties and film-forming ability, however, their hydrophobic long-chain fatty acids or alkanes, could compensate for the hydrophilicity of most plant proteins, thereby enhancing the water resistance of films (Hassan et al., 2018). These characteristics of lipids help to improve the comprehensive performance of protein-based composite films. Wang et al. (2014) studied the impact of various oleic and stearic acid ratios on the performance of SPI-based film, results found that the addition of above lipid significantly reduced the water vapor permeability (WVP) of the composite films, and its optimal barrier performance was achieved at a 2:3 mass ratio of oleic acid and stearic acid. Hopkins et al. (2015) incorporated 1, 3, 5, 7.5, and 10% w/w linseed oil (based on protein mass) into the SPI solution to

create edible composite films via solution casting method. They found that tensile strength (TS) of the composite films increased and was reached to a peak at 5% w/w oil concentration. The initial increase in TS is likely due to the formation of a stable emulsion where the protein acts as an effective emulsifier, promoting a more uniform film structure. However, excessive lipid incorporation of lipids into protein can tend to hinder film formation due to its poor film-forming ability and increased structural defects, leading to a decrease in mechanical strength. Further research is needed to optimize the incorporation of lipid biopolymers into packaging films and to explore their potential in food packaging.

### 3.4 Protein/protein

Protein-protein composite films can overcome the limitations of single protein films and enhance the comprehensive performance of composite films. However, protein-protein cross-linking is not as pronounced as interactions between proteins and other classes of substances, and therefore the research on protein-protein cross-linking is limited. Guo et al. (2012) created an edible composite film utilizing zein and wheat gluten protein, and the results showed that composite film exhibited favorable water vapor permeability (WVP) and mechanical properties. This enhanced performance is a result of molecular self-assembly and phase separation, where the highly hydrophobic zein segments preferentially locate at the external or internal interfaces, forming effective water barriers, while the viscoelastic wheat gluten provides mechanical resilience. In addition, the viscoelastic properties of wheat gluten protein enhanced elasticity while reducing elongation, thus weakened the brittleness of simple zein-based protein film. Cho et al. (2010) added a layer of zein film to SPI-based film, and found that the water vapor permeability (WVP) of the bilayer film decreased from  $0.94 \times 10^{-12}$  kg/(m<sup>2</sup>·s·Pa) to  $0.61 \times 10^{-12}$  kg/(m<sup>2</sup>·s·Pa), due to zein's abundant hydrophobic amino acids and its lower oxygen permeability (OP) compared to traditional synthetic film (linear polyethylene). This bilayer approach leverages the superior barrier properties of the hydrophobic zein layer (acting as the limiting factor for diffusion) and the structural integrity of the SPI layer. In a study reported by Kilincceker et al. (2009), zein and gluten were used to fabricate a composite coating for packaging trout fillets. The coatings, utilizing gluten as the first layer, xanthan gum as the second, and gluten-zein as the last, this protein/protein film provided better preservation than non-coated samples. However, varying protein types, ratios, as well as preparation methods may affect mechanical properties and packaging effectiveness (e.g., oxygen permeability and bacterial inhibition). Future research should focus on adjusting these factors and exploring new fabrication techniques to develop protein-protein composite films with superior performance and stability.

## 4 Fabrication technology of plant protein-based film/coating

Several techniques are available for preparing film/coatings on biodegradable materials, to achieve varying film properties such as gas resistance, water resistance, and mechanical properties for protein-based food packaging. The most common techniques used for fabricating film/coating are described briefly as follows.

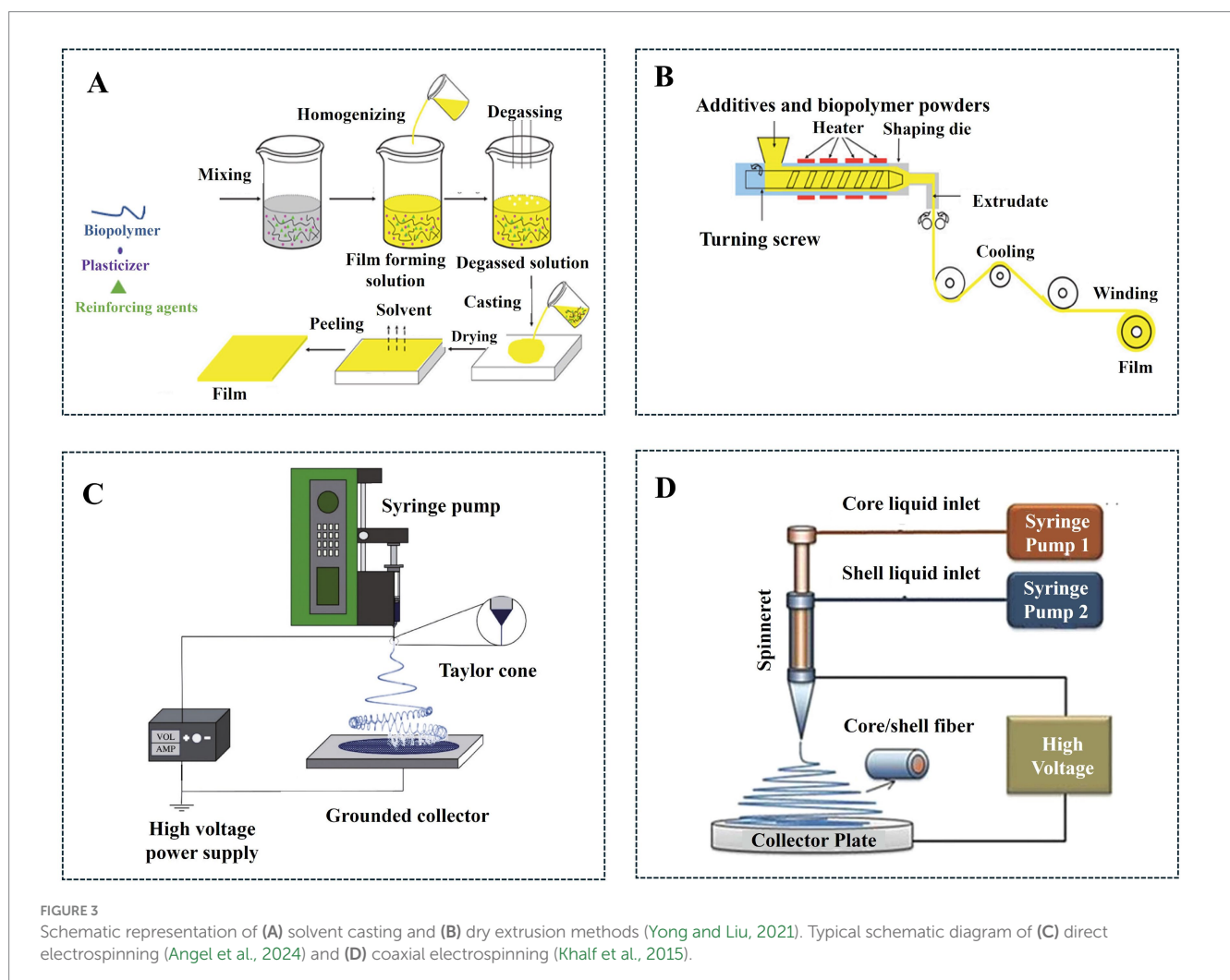
## 4.1 Solution casting method

The solution casting method refers to the process of dissolving plant protein and other functional additives (such as plasticizers and cross-linking agents) in a certain solvent to fabricate a film-forming liquid of a certain concentration. This mixture is then cast onto a flat surface for even distribution; the solvent phase is removed by evaporation and thereafter the dried film is released from the film-forming medium (Figure 3A). For instance, zein-zein/gelatin-gelatin (Z-ZG-G) multilayers were constructed via layer-by-layer solvent-casting method. This structure maximized zein's water-blocking property and gelatin's hygroscopic and moisture-retaining properties to achieve a unidirectional barrier to water molecules, thereby extending the shelf-life of food products (Xia et al., 2021). Another study revealed that soy protein concentrate (SPC) films prepared by solvent casting had better oxygen barrier properties compared to those made by compression molding (Ciannamea et al., 2014). The solution casting method is easy to execute, operates under mild conditions, and yields films with controllable thickness and good uniformity. Furthermore, this method enables precise regulation of single variables (e.g., solvent type), facilitating the investigation of how different components influence film properties. However, film formation takes longer time due to solvent evaporates slowly during

the process. In addition, the film is more difficult to peel off and usually requires a release agent.

## 4.2 Dry extrusion method

Dry extrusion is a prevalent technique for producing plant protein-based films. In a screw extruder, the plant protein raw material and other additives is heated and mixed until they form a viscous melt under the condition of controlling the moisture content of materials between 5 and 15% (Yong and Liu, 2021), the above materials was then extruded through a die and nozzle into a specific shape by adjusting the screw speed and die size, gradually solidified by cooling, and finally cut to the desired length and collected (Figure 3B). During the dry extrusion process, the hydrogen bonds and disulfide bonds between protein molecules are destroyed by screw shearing force to loosen the molecular chains. Then, the temperature is further increased to promote the re-crosslinking of protein molecules and the formation of a network structure until a viscous melt is formed. Asgher et al. (2020) fabricated wheat gluten films through intensive extrusion, in which wheat gluten is denatured by heating during extrusion, these processes resulted in the breakage of



hydrophobic and disulfide bonds, and the formation of new disulfide bonds during drying.

Films produced by this technique possess homogeneity, excellent gas barrier properties and high mechanical strength. Dry extrusion technique can also produce multilayer films via co-extrusion, where different polymers are co-extruded through separate screws to form their own polymer layers, thus enhancing film's functionality. Wang H. D. et al. (2024) and Wang S. M. et al. (2024) developed polylactic acid (PLA) multilayer film with clove essential oil (CEO) through the co-extrusion process. This technology ensured the uniform distribution of CEO within the different layers of multilayer film to minimize the loss of CEO and achieve its slow release, imparting effective antimicrobial and antioxidant activities to film. Winotapun et al. (2019) fabricated multilayer low-density polyethylene (LDPE) films containing polylactic acid (PLA) through co-extrusion technique. Their results found that this multilayer structure significantly improved aroma barrier and gas permeability of the composite film, this makes film suitable for modified atmosphere packaging to maintain the quality of fresh-cut durian during the storage.

Extrusion technology offers several advantages over solution casting method, including shorter processing times, lower energy consumption, and improved mechanical and optical barrier properties of edible films, such as elongation and transparency. However, the extrusion method is restricted to raw material blends that can withstand high temperatures and low moisture, and its specialized equipment is expensive and costly to maintain.

### 4.3 Electrospinning method

Electrospinning is a high-efficiency, cost-effective technique that utilizes electro-hydrodynamics to fabricate continuous polymeric nano-scale or micro-scale fibers. It includes direct electrospinning and coaxial electrospinning. For traditional direct electrospinning method, its working mechanism is that under the action of an external electric field, the polymer solution is deformed by force after being ejected through the filament nozzle of the syringe, which ultimately forms randomly displaced thin polymer fibers on different collection devices (Kalimuldina et al., 2020) (Figure 3C). Yuan et al. (2023) prepared nanocomposite fibers films using zein and gelatin as electrospinning solution, incorporating antimicrobial ZnO nanoparticles, antioxidants proanthocyanidins and gallic acid to enhance the shelf life of sweet cherries. The study revealed that all components were uniformly dispersed within the fibers, with effective inhibitory activity against pathogens and antioxidant properties. Wang H. D. et al. (2024) and Wang S. M. et al. (2024) highlighted how electrostatic spinning facilitates the continuous entanglement, fusion, and stretching of zein and millet gliadin molecules, producing zein/millet gliadin nanofibers with excellent mechanical properties. However, the electrospinning of biopolymers can be challenging due to their complex chemical structures and distributed molecular weights. For example, zein's spinnability is hindered by the rapid evaporation of solvents like ethanol, which lead to spinneret blockages with semi-solid substances.

In coaxial electrospinning, two or more types of polymers are dissolved as core and shell layer solutions and then injected into two concentrically aligned nozzles, and the same voltage induces composite droplet deformation in both nozzles. A jet flow is generated

at the tip of the deforming droplet, and subsequently produces core-shell fiber films (Lu et al., 2021) (Figure 3D). Zhang L. M. et al. (2019) and Zhang Y. B. et al. (2019) encapsulated antimicrobial agent-thymol in poly (propylene-co-glycolide) through coaxial electrospinning to create core-shell nanofibers. This core-shell structure effectively protected volatile thymol and control its slow release into the headspace above food, inhibiting bacterial growth on the surface of food. Additionally, researchers developed an antimicrobial packaging film by integrating cinnamon essential oil (CEO) into polylactic acid (PLA) nanofibers via coaxial electrospinning technique. They observed that coaxial electrospinning technique achieved greater CEO retention than with the casting technique, thus, electrospun nanofibrous film exhibited a larger inhibition zone diameter, exhibiting better antimicrobial activity (Wen et al., 2016). Electrospinning method produces films with a large specific surface area, high porosity and strong loading capacity, which effectively encapsulate antioxidants and antibacterial agents and give the films diverse applications. However, this method is costly, requires specialized equipment, and involves a complex process with multiple controllable parameters.

While both direct and coaxial electrospinning are powerful techniques for fabricating plant protein-based nanofiber films, they serve different functional goals and present distinct technical challenges. The choice between these two methods depends on the desired fiber structure and the functional components being incorporated. Direct electrospinning is preferred for simple structural reinforcement when the functional agent (e.g., nanoparticles) can be uniformly dispersed throughout the entire fiber matrix. Conversely, coaxial electrospinning is essential when protecting volatile components (e.g., essential oils, volatile antimicrobials) from harsh processing conditions or when controlling the release profile of an active agent is the primary objective.

## 5 The sustainability of plant protein-based films

For the food packaging, "sustainability" is defined by encompassing the ability of a material to minimize its environmental footprint across its entire lifecycle—from resource acquisition, production to usage to end-of-life disposal. For plant protein-based films, sustainability primarily relies on three aspects: renewable sourcing, rapid biodegradability, and reduction of embedded carbon footprint.

### 5.1 Renewable and biodegradable properties

Plant protein-based films/coatings offer inherent sustainability through renewable sourcing and complete biodegradability, providing a closed-loop alternative to petroleum-based plastics. Their biodegradation occurs via microbial enzymatic cleavage of peptide bonds, with degradation rates exceeding conventional plastics. Studies demonstrate that soy protein isolate (SPI)/wheat gluten films exhibit 50% mass loss within 10 days and >95% degradation within 30 days under composting conditions, which was significantly faster than disposable polyethylene films (Park et al., 2000). Similarly, zein-based

films also demonstrate accelerated breakdown due to their hydrophobic nature facilitating microbial access (Chen et al., 2020). Beyond their environmental benefits, plant protein films contribute to valorize agricultural byproducts. For example, wheat gluten protein (WGP) films can be produced from wheat milling byproducts; while corn-derived zein utilizes coproducts from the ethanol industry. This dual advantage of waste valorization and rapid decomposition positions plant proteins as key enablers of circular packaging economies. Adopting plant protein-based packaging would allow the food industry to reduce waste, conserve resources, and meet consumer demand for eco-friendly products.

## 5.2 Reduced carbon footprint

Plant protein-based films also offer a pathway towards significantly reduced carbon footprints through the utilization of renewable resources and biodegradable properties. Life cycle assessment (LCA) revealed their significant environmental advantages. A key study by Deng et al. (2013) demonstrated the substantial environmental advantage of wheat gluten films over low-density polyethylene (LDPE) packaging. Specifically, their analysis revealed that the production of wheat gluten film resulted in a climate change impact of approximately 205 g CO<sub>2</sub> eq per functional unit, which represents a remarkable 63.4% reduction compared to LDPE film (560.8 g CO<sub>2</sub> eq per functional unit). In terms of non-renewable energy use, wheat gluten film consumed only 2.4 MJ per functional unit, achieving a 70.7% reduction relative to LDPE film (8.2 MJ) and a 67.6% reduction compared to PLA film (7.4 MJ). This substantial reduction in carbon footprint establishes plant protein films as viable alternatives for sustainable packaging solutions.

## 6 Plant protein -based film for shelf-life extension of food products

### 6.1 Application in fruits and vegetables

Plant protein-based packaging presents a promising avenue for extending the shelf-life of food products (Figure 4), particularly for fruits and vegetables, which are vital sources of vitamins, minerals, and other nutrients. They are also rich in digestive enzymes and dietary fiber, which could promote gastrointestinal health, prevent constipation, and alleviate some problems such as bloating. However, the fruits and vegetables were easily to occur significant losses during daily transport and storage due to gas and water vapor permeation. Food packaging was an available tool to solve this problem, because it can reduce oxygen levels to decrease respiration, and minimize weight loss by blocking water vapor and extend shelf life. Yousuf and Srivastava (2019) utilized soy protein isolate (SPI) coating combined with honey to preserve fresh-cut pineapple, results found that the coating could inhibit bacterial growth, thereby extended the shelf life of fresh-cut pineapple by 16 days at 4 °C. Similarly, Liu R. et al. (2017) and Liu X. R. et al. (2017) developed an SPI-based nanocomposite film for apples, result showed that the film delayed the apples' climacteric peak until the fifth week under optimized conditions, and this film resulted in less than 12.08% weight loss after 4 weeks, due to its enhanced moisture barrier properties. Additionally, zein-based film

incorporated with chitosan was used for coating mushrooms, results suggested that this composite film effectively delayed the respiration rate and limited microbial growth during storage (Zhang L. M. et al., 2019; Zhang Y. B. et al., 2019).

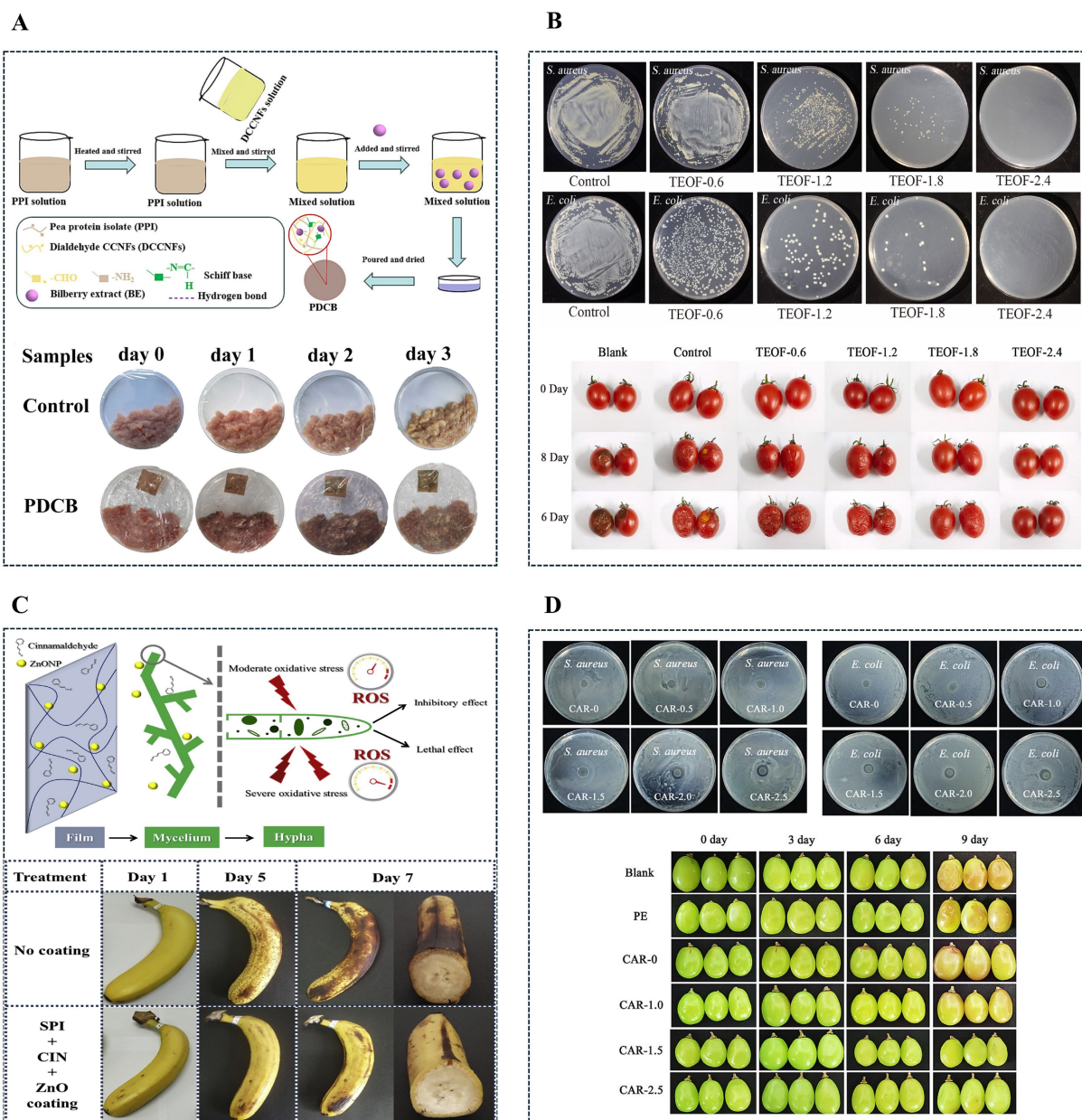
### 6.2 Application in meat products

Fresh meat and dairy products are nutrient-rich but susceptible to microbial growth and oxidation. Microorganisms will accelerate the breakdown of proteins and unsaturated fatty acids will be oxidized into peroxides under the action of oxygen, causing meat and dairy products spoilage (Hadidi et al., 2022). Thus, biopolymer packaging with effective oxygen barriers and antibacterial properties is crucial for preserving meat and dairy products. Najafi et al. (2020) developed the antimicrobial zein edible films loaded with eucalyptus leaf essential oil on preserving minced sheep meat. The authors observed that the developed packaging reduced lipid oxidation and extended the shelf life of minced sheep meat by 6 days. Alak et al. (2019) developed quinoa starch-based edible films (QSBF) to preserve rainbow trout fillets at 4 °C for 12 days. Microbial analysis revealed that QSBF-coated samples exhibited lower microbial counts compared to control group, which indicate its potential to inhibit germ growth. Tayebi-Moghaddam et al. (2021) developed a zein-based bio-film with 10% clove essential oil (CEO) to protect Iranian cheese against food fungi *L. monocytogenes* and *E. coli* O157: H7. This find revealed that the zein-based films loaded with 10% CEO significantly improved antimicrobial properties and were considerably successful in extending the shelf life of Iranian cheese.

### 6.3 Application in fried and baked foods

Fried foods like fried chicken, french fries, and instant noodles are popular in fast-paced lifestyles. But they tend to have serious oil absorption during the production process, making people prone to weight gain. Moreover, the oil is easily oxidized, causing changes in chemical properties, affecting their flavor, and even producing toxic or carcinogenic substances, which is harmful to human health. To address this, edible protein films with strong oil and oxygen resistance for pretreating fried products can not only effectively reduce the oil content in food, improve food flavor and color, but also delay oil rancidity and extend the shelf life of food. Cho et al. (2010) fabricated a composite edible packaging by laminating corn zein onto a soy protein isolate (SPI) layer and used it to package olive oil condiments for instant noodles. Their results demonstrated that this composite packaging was superior to synthetic film for storage of products, as it effectively reduced the oxidative rancidity of olive oil due to its superior oxygen barrier properties.

Despite there has been relevant research and have made some progress in food preservation with protein-based film (Figure 4). Research on plant protein films for food preservation is still far from enough. While intelligent indicators like anthocyanins and curcumin have been incorporated to detect pH changes and provide real-time color feedback on food quality (Kong et al., 2023; Roy et al., 2022). However, studies on intelligent, responsive plant protein-based films are scarce, it primarily focuses on pH response. It is essential to



**FIGURE 4** Examples of plant-based film/coating. (A) The intelligent packaging film of pea protein isolate cross-linked with dialdehyde carboxylated cellulose nanofibers for pork freshness monitoring (Zhang et al., 2024). (B) Appearance of cherry tomatoes coated with thyme essential oil composite film based on soy protein isolate (Liu et al., 2024). (C) Evaluation of banana postharvest quality using a bio-nano composite coating of soybean protein isolate/cinnamaldehyde/zinc oxide (Li F. et al., 2019; Li J. M. et al., 2019). (D) The composite film of carvacrol/soybean protein isolate applied for grape preservation (Liu et al., 2025).

produce composite films with diverse properties for various purposes, giving full play to the advantages of composite edible film.

In the future, exploring novel plant protein sources and fully understanding their functional properties will aid in developing multifunctional protein composite films that can meet various needs. Furthermore, developing plant protein-based intelligent packing, and deeply exploring the mechanism of various bioactive compounds incorporated into films, which can inform the creation of innovative packaging types, such as climate-controlled packaging, active packaging, intelligent packaging that tailored for specific food applications.

## 7 Conclusion and prospective

Although plant protein-based films have demonstrated remarkable potential, many developments still remain at the lab stage and have not yet transitioned to large-scale food industry applications. Currently, the commercial application of these films is primarily focus on some field, such as edible coatings for extending the shelf-life of fresh produce (e.g., fruits and vegetables), biodegradable casings for meats, and water-soluble sachets for dry ingredients (e.g., seasoning blends and instant beverages). These applications leverage the proteins'

inherent gas barrier properties and biodegradability to replace single-use synthetic plastics in specialized contexts.

In the future, plant protein-based films are emerging as a sustainable solution for several markets. A particularly promising field is the burgeoning plant-based meat and dairy alternative industry, where consumers demand packaging that aligns with the product's environmental and sustainability. The quick-service restaurant (QSR) field also presents a significant market for edible wrappers and condiment pouches, enabling zero-waste consumption. These films' potential extends to active and intelligent packaging. By incorporating bioactive compounds (e.g., natural pigments as pH sensors or essential oils as antimicrobials) directly into the protein matrix, these films can transform into functional systems that monitor food freshness or actively inhibit microbial growth, thereby reducing food waste.

## Author contributions

LW: Writing – original draft, Writing – review & editing. XW: Writing – review & editing, Investigation. YL: Writing – review & editing. QJ: Software, Investigation, Writing – review & editing. ZW: Funding acquisition, Conceptualization, Supervision, Writing – review & editing.

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## Conflict of interest

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