coatings

Review

Protein-Based Films and Coatings: An Innovative Approach

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Abstract: Protein-based films and coatings are highly biodegradable and represent sustainable alternatives to petroleum-based materials. These materials possess commendable barrier properties, effectively safeguarding against oxygen, moisture, and aroma compounds, rendering them well-suited for various food packaging applications. Beyond their role in food packaging, coatings and films have significant applications in the biomedical and pharmaceutical domains. Their inherent biocompatibility and controlled release properties make them valuable for applications such as drug-delivery systems, wound dressings, and tissue-engineering scaffolds. Moreover, the adaptability of these films to exhibit stimuli-responsive behavior opens avenues for on-demand drug release and sensing capabilities. Despite these promising attributes, challenges persist in terms of the mechanical strength, water resistance, and scalability of the processing of protein-based films and coatings. Ongoing research endeavors are dedicated to refining protein extraction methods, incorporating reinforcing agents, and implementing strategies to optimize the overall performance of these materials. Such efforts aim to overcome existing limitations and unlock the full potential of protein-based films and coatings in diverse applications, contributing to the advancement of sustainable and versatile biomaterials.

Keywords: barrier properties; food packaging; coatings; films

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1. Introduction

Films and coatings prepared from protein are gaining keen interest from researchers because of their easy handling, utilization in packing, usefulness in the shelf-life enhancement of fruits, and advantages over synthetic films/coatings [1]. The broad spectrum of uses of protein-based films and coatings make them a good choice for commercial-scale operations. Films and coatings prepared using protein could also be utilized as a carrier to deliver antioxidant- and antimicrobial-rich formulations [2]. Protein is one of the important macromolecules that exist in natural resources in two different forms (globular or fibrous). Globular protein has good solubility in water as well as aqueous solutions of salts and acid bases. Fibrous protein is considered as water insoluble and plays a vital role in providing structural support. Both forms of protein are important for sustaining the routine functioning within the body of living organisms. The physical and chemical features of protein depend on the concentration of amino acid residues and their amendment in polymer chains [3]. Collagen (fibrous) is widely being utilized in the synthesis of edible films [4]. The characteristic features of films prepared from protein of different sources (mung bean, corn zein, gelatin, wheat gluten, whey protein, soy, and gelatin) have been well documented [5–8]. Protein-based films prepared from different sources are presented in Tables 1 and 2. Food packaging trends are shifting from traditional packing (metal, glass, polymers, and paper) to edible or biodegradable material. Researchers are now focusing on the enhancement of the shelf-life of eatable materials using nutrient components isolated from either other foods or food residue [9]. However, the tear and tensile strength is one of determinant factors which should be kept in mind before preparing such coatings or films. Utilizing the biodegradable coatings/films for packing and shelf-life enhancement open up a new era, as its use does not cause any serious ecological issues. The application of protein-based coatings/films in different sectors generated our interest to write this review paper. In this review, the authors have tried their best to cover the different aspects, like the application and the role of protein-based films/coatings in different sectors. This review paper helps to fill the remaining gap related to protein-based coatings/films in-between the existing knowledge on this topic.

Table 1. Properties of protein-based films prepared using different resources.

Type of Film	Ultimate Strength (MPa)	Thickness (µm)	Water Content (%)	Water Vapor Permeability	References
Silk protein-based film	0.4–19	--	--	--	[10]
Whey protein–kefiran composite films	3.16–3.95	129.9–153.3	24.44–28.80	--	[11]
Whey protein–cellulose nanocrystal packaging films	--	166.05–173.2	14.84–18.05	2.82–3.18 ($g{\cdot}s^{-1}{\cdot}m^{-1}{\cdot}Pa^{-1}$)	[12]
Whey protein-based edible film	0.7–1.8	100–160	--	6.2–12.8 ($g{\cdot}mm/d{\cdot}m^2{\cdot}kPa$)	[13]
Soy protein isolate/sodium alginate edible films	3.52–7.12	--	--	3.55–5.15 ($g{\cdot}mm/(m^2{\cdot}h{\cdot}kPa)$)	[14]
Soy protein isolate film	7.09–7.88	--	--	0.86–1.19 ($\times 10^{-10}$ $g{\cdot}m^{-1}{\cdot}s^{-1}{\cdot}Pa^{-1}$)	[15]
Soy protein-isolate-based film	2.01–4.4	150–180	11.4–14.5	--	[16]
Soybean protein isolate films	--	126–232	17.93–20.11	0.60–0.76 ($g{\cdot}mm\ h^{-1}\ m^{-2}\ kPa^{-1}$)	[17]
Faba bean protein films	4.8–9.3	258.7–372.5	13.7–15.5	--	[18]
Graphene oxide/cinnamon bark oil nanocomposite packaging films	8–23	19–29	0.06–0.10	1.3–2.9 ($\times 10^{-10}$ $g\ m^{-1}\ s^{-1}\ Pa^{-1}$)	[19]
Wheat gluten protein films	--	47.89–69.37	1.73–2.13	7.16–17.07 ($(g{\cdot}mm)/(m^2{\cdot}d{\cdot}kPa)$)	[20]
Edible films from the protein of a brewer's spent grain	--	--	17.7–29.69	3.03–4.58 ($g{\cdot}m/m^2{\cdot}s{\cdot}Pa$) $\times 10^{-10}$	[21]
Almond protein isolate films	5.55–12.77	104–126	--	165–166.1 ($\times 10$ $g\ m^{-1}\ s^{-1}\ Pa^{-1}$)	[22]
Composite films based on egg-white protein	--	--	9.38–13.95	--	[23]

Table 2. Gelatin-based films for various purposes.

Source	Purpose	References
Gelatin	Utilizing gelatin as a bioactive nanodelivery system for applications in functional foods	[24]
Gelatin-based coating	A gelatin-based coating film reinforced with multifunctional carbon dots for the preservation of strawberries	[25]
Acylated pectin/gelatin-based films	Characterization of acylated pectin/gelatin-based films containing alkylated starch crystals: Assessment of antioxidant and antibacterial activities, and examination of coating preservation effects on golden pomfret	[26]
Fish gelatin	Preparation, characterization, and application of emulsifier-free fish gelatin-based films exhibiting outstanding antioxidative and antibacterial activity for coating preservation of fish fillets	[27]

Table 2. *Cont.*

Source	Purpose	References
Gelatin/agarose-active coatings	Formulation of gelatin/agarose active coatings incorporating *Ocimum gratissimum* L. essential oil to improve the storability of 'Booth 7' avocados	[28]
Fish gelatin	A novel edible coating comprising fish gelatin infused with açaí oil to extend the postharvest shelf-life of tomatoes	[29]
Gelatin–TiO_2–Al_2O_3 nanocomposite	Impact of gelatin-TiO_2-Al_2O_3 nanocomposite coatings on improving the wear and corrosion resistance of SKD11 steel	[30]
Fish gelatin	Creation of electrospun fish gelatin film incorporating lauroyl arginate ethyl and its utilization in the preservation of large yellow croaker (*Pseudosciaena crocea*)	[31]
Gelatin	Environmentally promising food packaging utilizing a photodynamic-responsive gelatin-based coating with high-utilization curcumin-loaded bilayer nanoencapsulation	[32]
Furcellaran–gelatin	Formulation of active double-layer gel coatings using furcellaran-gelatin and aqueous butterfly pea (*Clitoria ternatea*) flower extract to extend the shelf-life of salmon (*Salmo salar*)	[33]
Nanocomposite gelatin	Creation of a nanocomposite gelatin-based film using Pickering emulsion containing chitin nanoparticles	[34]
Gelatin	Advancements in gelatin-matrix composite films: The incorporation of vitamin C adducts improves the optical characteristics of gelatin films	[35]
Gelatin-coated ZnNPs	Coating of biodegradable biopolymer films with organic gelatin-encapsulated ZnNPs	[36]
Fish gelatin	Utilization of fish gelatin films containing cinnamaldehyde and its sulfobutyl ether-β-cyclodextrin inclusion complex, with application in fish preservation	[37]
Cellulose–gelatin	Innovative cross-linking of nontoxic biopolymers for cellulose-gelatin films derived from waste avocado seeds	[38]
Chicken gelatin	Optimization and characterization of biodegradable films made from chicken gelatin crosslinked with oxidized phenolic compounds	[39]
Gelatin–sodium alginate	Eco-friendly packaging for extending the shelf-life of raw minced beef using a gelatin-sodium alginate film incorporated with date pits extract	[40]
Gelatin-based hydrogel	Customizing the surface and rheological properties of hydrogel films based on gelatin through indirect cold plasma treatment for engineering applications	[41]
Chitosan–gelatin	A holistic approach to edible coating with chitosan-gelatin incorporating β-cyclodextrin/lemongrass essential oil inclusion complex—Characterization and application in the food industry	[42]
Cellulose/gelatin-carboxymethyl chitosan	Bilayer films of ethyl cellulose/gelatin-carboxymethyl chitosan, enriched with polyphenols from Euryale ferox seed shells, for the preservation of cooked meat	[43]
Gelatin	Influence of various nanocellulose types on the structure and characteristics of gelatin films	[44]
Gelatin/sodium carboxymethyl cellulose	The direct incorporation of vanillin enhanced the physicochemical properties and antibacterial activities of gelatin/sodium carboxymethyl cellulose composite films	[45]
Carboxymethyl chitosan–gelatin	A novel transparent film wound dressing composed of carboxymethyl chitosan-gelatin-mesoporous silica nanoparticles incorporating *Myrtus communis* L. extract	[46]
Chitosan–gelatin	Influence of an edible coating comprising chitosan-gelatin with nano-encapsulated clove ethanol extract on the cold storage of chilled pork	[47]
Polyurethane/gelatin film	Antibacterial films for strawberry packaging using waterborne polyurethane/gelatin based on castor oil	[48]
Gelatin–sodium caseinate	Creation of a high-oxygen-barrier film comprising gelatin and sodium caseinate, enriched with elderberry (*Sambucus nigra* L.) extract, and assessment of its antioxidant capacity on pork	[49]
Chitosan–fish skin gelatine	Impact of edible coatings made from chitosan and fish skin gelatin containing black tea extract on the quality of minimally processed papaya during refrigerated storage	[50]
Chitosan–gelatin	Impact of blending and layer-by-layer assembly techniques on chitosan–gelatin composite films enhanced with curcumin nanoemulsion	[51]
Gelatin	Formulation and characterization of an active packaging film based on gelatin loaded with eugenol nanoparticles, with application in the preservation of chicken	[52]
Gelatin–serum	Gelatin-serum plasma film infused with curcumin to enhance antioxidant and antibacterial properties for application in fresh pork packaging	[53]
Gelatin	Innovative "all-in-one" multifunctional gelatin-based film designed for the preservation and monitoring of beef freshness	[54]
Gelatin/chitosan-based film	Preservative impact of films based on gelatin and chitosan infused with lemon essential oil on the storage of grass carp (*Ctenopharyngodon idellus*) fillets	[55]
Alginate–gelatin	Prolonging the shelf-life of cheese through the use of eco-friendly sodium alginate-gelatin films reinforced with nanoclay	[56]
Gelatin	Cross-linked gelatin film enhanced with green carbon quantum dots for bioactive food packaging	[57]
Starch/gelatin	Impact of various natural wax types on the physicochemical properties of starch/gelatin edible films produced through extrusion blowing	[58]
Gelatin	Analysis of the thermal behavior and structural properties of a commercially produced high-solids confectionery gel containing gelatin	[59]

2. Historical Development

Films/coatings are being prepared to create a barrier between the fruit surface and the environment so that they can protect the fruits from damage due to moisture loss [60,61]. Such fruitful formations to protect the edible materials are recorded in Japan, where 15th-century films/coatings were prepared to preserve the food. These films were prepared using soymilk. Protein-based edible films and coatings have undergone significant historical development, with advancements made over several decades. The exploration of proteins as materials for food packaging began in the 1960s, as researchers sought biodegradable alternatives to traditional plastic packaging. Proteins were identified for their abundance, biodegradability, and food safety. During the 1970s, casein, a protein derived from milk, was one of the earliest protein sources used to create edible films. Casein films exhibited favorable mechanical properties and barrier characteristics, making them suitable for packaging dairy products, like cheese and butter [62,63]. In the 1980s, soy protein isolates gained attention as a viable option for edible coatings and films. Soy protein films showed improved flexibility and mechanical strength. They were employed in extending the shelf-life of fruits, vegetables, and meat products. In the 1990s, collagen, a protein found in animal tissues, was explored for its film-forming purposes. Collagen films displayed excellent transparency and gas barrier properties, making them suitable for packaging meats and seafood. Throughout the 2000s, researchers focused on enhancing the processing techniques for protein-based films and coatings. Methods such as solvent casting, extrusion, and casting with edible plasticizers were refined to achieve improved film properties, uniformity, and manufacturing efficiency. Recent advancements have focused on developing protein-based films and coatings with additional functionalities. These include incorporating antimicrobial agents, antioxidants, and bioactive compounds to enhance the food safety and prolong the shelf-life. These innovations have opened up possibilities for intelligent packaging solutions with enhanced functionality. Researchers have also explored alternative protein sources for film-forming materials. This includes proteins derived from agricultural byproducts, like wheat gluten, corn zein, and rice bran proteins. These alternative sources offer the potential for the sustainable and cost-effective production of edible films. Protein-based edible films and coatings have found commercial applications in various food industries. They are utilized for packaging a wide range of products, including baked goods, snacks, confectionery, and fresh produce. Additionally, they act as edible barriers to control moisture, oxygen, and flavor transfer in food systems.

Understanding gelatin-based coatings and films involves delving into the historical development and evolution of materials derived from gelatin across diverse applications. Derived from animal collagen, gelatin has found utility in the food industry, in pharmaceuticals, and in other domains. Gelatin boasts a rich history, with indications of its utilization in food and medicinal contexts [7,64]. Gelatin's prevalence endured in pharmaceutical formulations, extending to coatings for tablets and capsules. The late 20th century marked a significant uptick in the utilization of gelatin in coatings and films. These applications were explored in the realm of controlled-release drug-delivery systems, where gelatin coatings allowed for the gradual release of drugs over time [65–68]. Simultaneously, gelatin-based films gained traction in the food packaging industry due to their biodegradability and effective barrier properties [6,69,70]. Researchers are actively investigating methods to modify gelatin through chemical or physical processes, tailoring its properties for specific applications. The biodegradability and comparatively low environmental impact of gelatin have heightened its appeal in sustainable packaging solutions. Ongoing research endeavors aim to broaden the scope of applications for gelatin-based coatings and films, exploring innovative formulations and processing techniques. The sustainability and biocompatibility of gelatin position it as a promising material for future advancements in areas such as food packaging, drug delivery, and the development of biodegradable plastics [35,71–74]. As the demand for sustainable packaging continues to rise, the development of protein-based edible films and coatings is an area of ongoing research [1,75]. Efforts aim to improve their mechanical properties, barrier characteristics, and functionality to meet the evolving needs of the food packaging industry.

3. Improvement of Protein-Based Films and Coatings

Thin layers of edible or nonedible proteins can be used as protein-based films or coatings on food or other surfaces. There may be certain drawbacks of biodegradable materials (coating/films), such as the low mechanical strength and water barrier qualities [76,77]. The qualities of coatings/films based on proteins can be enhanced using a variety of formation techniques, as shown in Figure 1 and Table 3.

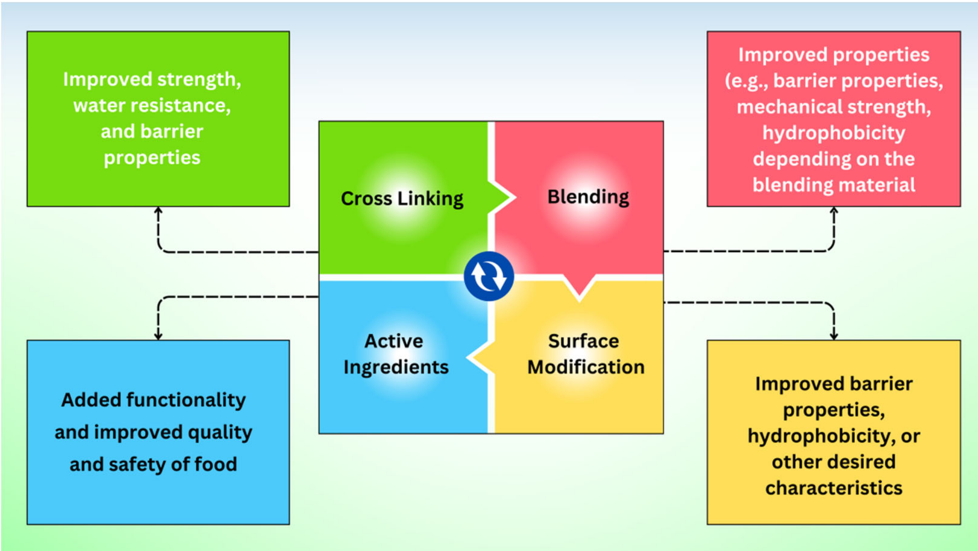

Figure 1. Representation of protein film/coating modification.

Table 3. Prevalent techniques of protein modification for film and coating applications.

Protein	Method of Film Formation	Modification/Additive	Observation	Reference
Canola meal-derived protein isolates	Solvent casting	Using fillers (oleic acid(OA)-modified (NCC) (OA-NCC))	OA-NCC enhanced the canola protein nanocomposite film tensile strength by 3%. The OA-NCC 7% nanocomposite films increased the break elongation by 130%. The protein and OA-NCC cohesion increased the thermal stability and water barrier properties.	[78]
Soy protein isolate	-	Free-radical polymerization (temperature, 60 °C; time, 2 h; initiator, AIBN)	The multifunctional soy protein (SP)-based adhesive had a strong bonding, with a good coating and pressing strength for the wet veneer. The pressing strength was 0.45–0.85 MPa, the bond strength was 0.35–0.65 MPa, the water contact angle was 105$^{\theta}$, and the oil contact angle was 115$^{\theta}$.	[79]
Whey protein concentrate (WPC) and carboxymethyl cellulose (CMC)	Solvent casting method	Modified by transglutaminase (TG) (concentration—0.5, 1, 1.5%; pH—−7; casting temperature—25 °C)	CMC as a protein network filler increased the WPC film characteristics, while TG improved the mechanical qualities. Compared to the WPC film, the composite (1:1) film with 10 U/g protein of TG had a maximum tensile strength of 13.34 MPa.	[76]
Crambe protein isolates (CPI)	Compression molding	pH modification (pH of 4–10)	Chemical modification of CPI increased the cross-linking by 20%, increased the tensile strength by 15%, and decreased the water vapor permeability by 10%.	[80]
Myofibrillar protein	Casting method	Changing the strength of the interaction between a protein and a filler material	Superior mechanical and water barrier properties using nanocrystalline cellulose, which improved the mechanical strength (elongation at break: 94.43% and tensile strength: 6.68 MPa) and the water vapor barrier (10.01×10^{-9} g m^{-1} s^{-1} Pa^{-1}).	[81]
Quinoa protein	Casting method	pH modification	Antibacterial and antioxidant properties of the film decreased with improved physicochemical and structural properties.	[82]
Soy protein isolates	-	Conformation modification	Strengthened the hydrophobic interaction, which created a strong network structure and increased the SPI-based film-storage stability and tensile strength.	[83]

3.1. Chemical Treatment

Cross-linking is an extremely effective technique for enhancing a film's mechanical strength, cohesiveness, water resistance, and water barrier qualities [84]. Several protein functional groups can be cross-linked. Protein networks can interact with many different kinds of active substances [85]. Functional groups use their reactive side groups as a means of accomplishing this. The functional qualities of the films can be improved by altering this by chemical, physical, or enzymatic cross-linking [86]. Theoretically, a longer chain structure with reduced permeability and a higher tensile strength should result from the increased protein interaction after the chemical treatment [87]. The soy protein isolate's tensile strength, oxygen permeability, and water vapor permeability were not affected by the alkaline treatment, but the films became more clear/uniform and had fewer air bubbles [88]. Aldehydes, such as glutaraldehyde, glyoxal, and formaldehyde, along with other naturally occurring cross-linking chemicals, have been utilized as chemical agents to covalently cross-link proteins [85]. Formaldehyde serves as a valuable cross-linking agent with a broad reaction specificity, effectively utilized in protein films. It interacts with the side chains of cysteine, tyrosine, histidine, tryptophan, and arginine, along with the amine group of lysine. Formaldehyde is a compound with a single functional group, although it can undergo bifunctional reactions and cross-linking as a consequence. Glutaraldehyde reacts with lysine, cysteine, histidine, and tyrosine, but it is more selective than formaldehyde. Glyoxal uses the side chain groups of arginine and lysine at an alkaline pH to cross-link the proteins [84,88].

Essentially, the interaction between formaldehyde and proteins comprises two steps: the initial formation of the methylol molecule, followed by the subsequent creation of methylene bridges. These bridges serve as cross-links between protein chains. A study revealed the impact of aldehyde cross-linking on the characteristics of films rich in gluten [89]. They found that the incorporation of cross-linking agents, like formaldehyde, glutaraldehyde, and glyoxal, decreased the water vapor permeability values of films rich in glutenin by approximately 30%. Formaldehyde produced the highest tensile strength values, followed by glutaraldehyde and glyoxal [90].

3.2. Enzyme-Based Treatment

Edible films derived from proteins demonstrate excellent barrier properties against gases, organic vapors, and oils. They are more environmentally friendly because they can be composted and biodegraded. They can be safely used in food packaging because they are edible and nontoxic. They can be altered to have a wide range of useful characteristics, including UV-blocking, antibacterial, and antioxidant capabilities. However, protein films' limited use as a packing material is due to their poor mechanical properties and high water permeability [91]. Numerous studies have focused on improving the functionality of protein-based edible films. Through the cross-linking of polymer chains, it becomes feasible to modify the polymer network and enhance the overall performance of these films [82]. Enzymatic cross-linking techniques are one efficient way to enhance the mechanical strength and barrier characteristics of protein-based edible films. Enzymes, such as lipoxygenase, lysyl oxidase, polyphenol oxidase, transglutaminase, and peroxidase, have been employed to cross-link proteins [76]. However, a specific enzyme capable of catalyzing covalent cross-linking processes between proteins, resulting in the formation of high-molecular-weight (MW) biopolymers, is known as transglutaminase. A glutamine residue's gamma-glutamyl amide link is broken by the TGase enzyme, creating a gamma-glutamyl thioester intermediate. An isopeptide bond is created when the gamma-glutamyl thioester intermediate combines with the epsilon amino group of a lysine residue on another protein [92].

The ε-amino groups of lysine residues (acyl acceptor) and λ-carboxy amide groups of glutamine residues (acyl donor) catalyze acyl transfer reactions [93]. The transglutaminase polymerization of casein, soy proteins, and gelatin, among other protein sources, has been documented [94,95]. Experimental conditions and the sources of protein were found to affect the gel strength differently. The order and strength of the cross-links created, as well as new covalent linkage degree, could obstruct the "physical" cross-linkages that occur during the renaturation and the triple helix during gel formation, which determined the improvement in the protein gel strength subjected to transglutaminase activity [96]. Transglutaminase can successfully introduce covalent bonds into films made from gluten that have been slightly aminated. The formation of covalent bonds resulted in the synthesis of high-molecular-weight polymers, potentially contributing to the heightened insolubility and reduced hydrophobicity. Mechanical characteristics promulgated by the application of transglutaminase resulted in the formation of covalent bonds, which improved the film's strength, durability, and stretchability [97].

3.3. Irradiation Treatment

The utilization of radiation for inducing cross-linking was found to be a valuable technique in improving the barrier and mechanical properties of polysaccharides and edible films [98]. Radiation generally modifies the conformation of proteins, oxidizes amino acids, breaks covalent bonds, and produces free radicals within the protein. Electrostatic and hydrophobic interactions, the creation of disulfide bonds, and interprotein cross-linking reactions can all turn proteins into higher-molecular-weight aggregates. Radiation has the potential to harm DNA, and one way it achieves this is by producing free radicals. Extremely reactive chemicals, known as free radicals, have the ability to damage other molecules, including proteins. Free radicals can cause proteins to unfurl and reveal their intrinsic disulfide links when they attack them. Higher-molecular-weight aggregates can then be formed by the reaction of these disulfide bonds with one another. Additionally, radiation can directly cross-link proteins. Numerous processes, such as the creation of noncovalent bonds like hydrogen bonds and hydrophobic interactions, as well as the development of covalent bonds between amino acid side chains, can cause this [99]. Exposing solutions that form films to radiation can modify the molecular characteristics of proteins through the generation of hydroxyl and superoxide anion radicals [87,100]. The creation of covalent cross-linkages in the protein solution following irradiation could account for the observed alterations in the protein films. At lower doses, there was the minimal formation of high-molecular-weight aggregates, but a noticeable increase was observed at higher doses. Radiation treatments, including gamma irradiation, have been employed to modify proteins with the intention of improving protein films [101]. To increase the milk protein films' chemical stability and water vapor permeability, gamma irradiation cross-linking can be employed. The outcomes demonstrated that resistance towards enzymatic and microbial biodegradation was enhanced and water vapor permeability was significantly ($p < 0.05$) decreased upon gamma irradiation (200 Gy) [102]. Additionally, there was a noticeable rise in the amount of high-molecular-weight proteins in the film-forming solution. Two theories could account for the impact on proteins by gamma irradiation: (i) more molecular residues engaged in the interactions between molecules; (ii) the development of covalent cross-links between and/or within molecules in the film-forming solutions [103].

3.4. Modification Using Hydrophobic Material

Protein films typically possess good mechanical qualities. However, protein films are less effective moisture barriers due to their hydrophilic nature [104]. Lipid films, on the other hand, function well as moisture barriers, but have a waxy taste, are typically opaque, and are relatively inflexible and unstable. A multicomponent system that combines lipids to act as a moisture barrier and proteins to create a continuous, cohesive network improves the performance of the films [105]. Lipids have the capacity to disperse within the hydrocolloid matrix, resulting in the formation of emulsified films, or they can create a layer over it, leading to the development of bilayer films. Emulsified films have garnered more attention compared to bilayer films. Two models have been proposed to explain the transfer mechanism through emulsified films [84]. In the "microvoid model," the mass transfer of gases and vapors occurs through microvoids that emerge during emulsion drying. These microvoids form between the microparticles of the hydrophobic material and the hydrocolloid matrix [5]. Another model, the "micro pathway model," posits an alternative explanation. In this model, mass transfer occurs through the high polymer matrix itself. This phenomenon arises because proteins often offer minimal resistance to the passage of gases and moisture, and they are frequently highly compatible with these elements. The addition of lipids to protein films has the potential to introduce flexible domains within the film and/or disrupt interactions between polymer chains. Additionally, lipids may influence the mechanical properties of protein films due to their limited cohesive structural integrity. The incorporation of beeswax (5%–10%) significantly enhanced the moisture barrier of films made from wheat gluten (70%) [2]. The combination of wheat gluten protein and diacetyl tartaric ester monoglycerides not only improved tensile strength, but also maintained clarity and reduced water vapor permeability. In a laminated whey protein–lipid film, the water vapor permeability decreased by a factor of 70 compared to the whey protein film. Giosafatto et al. [94] and Wu et al. [95] engineered composite films, encompassing laminate and emulsion films, by combining whey protein isolate and lipids to augment the resistance against water vapor. The emulsion films exhibited a water vapor permeability that was merely half of that observed in the isolated components. The lipids functioned as an apparent plasticizer, thereby improving the fracture resistance of the emulsion films [82]. Brazilian elemi, a highly hydrophobic resinous oil, was blended with stearic and palmitic acids and incorporated into a gelatin film. Triacetin served as the plasticizer in all the resulting films, and their physicochemical properties were evaluated. However, the introduction of lipids led to an increase in the opacity and soluble matter, accompanied by a decrease in the mechanical resistance [90].

4. Physiochemical Properties

The physical and chemical characteristics of protein-based edible films and coatings are closely associated with their plasticization properties, mechanical features, thickness, moisture content, water vapor permeability, sensory attributes, and environmental compatibility. In a study conducted by Bourtoom [106] on mung bean protein films, parameters such as the heating temperature and pH were identified as having the most significant impact on the film's qualities, with a correlation to the heating time. The study revealed that, at a pH of 9.5 and a temperature of 75 °C, the tensile strength reached its highest (5.70–6.51 MPa), while the elongation at break was at its lowest (32.06%–40.08%). Under these conditions, the protein content ranged from 19.26% to 27.00%, the film solubility was between 37.53% and 39.43%, and the water vapor permeability ranged from 11.37 to 16.91 g· mm/m^2 day kPa, all at their lowest levels. As the heat temperature and pH of the film solution increased, the color became more yellow and darker [106].

The moisture content of the packaging plays a pivotal role in both extending the shelf-life of a product and determining its water permeability. This is also influenced by the active components within the film or coating. For instance, the residual moisture level after the drying process affects the rate at which probiotics maintain viability during prolonged storage and aids in the dissolution of edible films in the mouth [107]. The moisture content of edible films significantly affects their physical, mechanical, and barrier properties. Edible films are thin layers of edible materials utilized to wrap or coat food products, providing protection, preservation, and sometimes enhancing the sensory attributes. The effect of the moisture content on the properties of edible films can vary depending on the specific composition of the film and substrate components. The moisture content can affect the tensile strength and elasticity of the film. In some cases, an increase in the moisture content may lead to a decrease in the tensile strength and an increase in the elasticity, making the film more pliable. Increased moisture content may lead to a higher WVP, reducing the film's ability to act as an effective barrier against water vapor. The moisture content affects the film's sorption capacity, impacting its ability to maintain the quality and stability of the enclosed food product. Excessive moisture content may create a favorable environment for microbial growth, potentially reducing the shelf-life of the food product. Scientific reports also suggest changes in specific parameters per the protein type used, formulation, and experimental conditions [10–23].

4.1. Mechanical Characteristics

Ensuring the mechanical strength and extensibility of protein-based films or coatings is essential for preserving the shelf-life of food products. Processing, packing, and storage are the first tests for package resistance and food protection [108,109]. The mechanical properties of films or coatings are affected by structural imperfections, modifications in key protein-based packaging components, the dispersion and density of intra- and intermolecular interactions among polymer chains, and the type and number of plasticizers [110].

Glycerol, as a plasticizer, plays a crucial role in influencing the mechanical properties of protein-based food-protection films. It reduces intermolecular tensions within the polymer, leading to a decrease in the tensile strength and an increase in the elongation at break [111]. A hole and the presence of a cavity can reduce the flexibility of a film or coating. To safeguard food and withstand production, handling, and storage stress, protein-based containers must have high mechanical qualities. According to Gialamas et al. [112], the reduced mass of probiotics had minimal impact on the tensile strength, the elongation at break, and the modulus of elasticity of the protein-based edible films. However, due to their mechanical resilience, cellulose-based edible films are more susceptible to the inclusion of probiotic cells.

Edible films were manufactured using a screw extruder, combining glycerol-plasticized thermoplastic pea starch (TPS) with either microcrystalline cellulose (MC) or carboxymethyl cellulose (CMC). The biodegradable polysaccharide underwent analysis, revealing an increased glass transition temperature and coefficient of elasticity. The incorporation of microcrystalline cellulose enhanced thermostability, whereas carboxymethyl cellulose had the opposite effect. The combination of MC and CMC resulted in an increased elongation at break at a 13% water content and a higher tensile stress. These changes were attributed to the notable relationship between starch and cellulose derivatives, as elucidated by Ma et al. [113].

4.2. Thickness

The thickness, water vapor permeability, transparency, and mechanical properties of protein-based films are interconnected. The thickness of a protein-based film is influenced by factors such as the preparation method, operational parameters (e.g., pH), and drying conditions (e.g., temperature) [114]. Soukoulis et al. [115] observed that the addition of L. rhamnosus GG cells to probiotic-containing edible films did not alter the thickness. However, in contrast, Soukoulis et al. [115] reported that probiotics in film-forming solutions affected the film's thickness. Another study incorporating L. casei into whey-based films demonstrated a direct impact on the film thickness [116]. There is variability in the findings, as Pereira et al. noted no change in the film thickness when introducing *B. animalis* or *L. casei* to the whey edible films [117]. This characteristic appears to have no discernible effect on the optical properties or water solubility. In the case of fish myofibrillar-protein-based packaging, the relaxation coefficient and film thickness did not influence the elongation at the break, but they did affect the break resistance [118].

4.3. Water Vapor Permeability

Water vapor permeability (WVP) is influenced by several factors, including the polymer chain mobility, film thickness, and overall film integrity. However, the literature predominantly focuses on the type and quantity of the plasticizer as the most commonly addressed factors. The notable advantage of heightened water vapor permeability is the increased solubility of films derived from proteins. This attribute is directly linked to an improved release of bioactive substances from modified or active packets that can be integrated into the protein-based film [19,119].

4.4. Biodegradability

Protein blends give biodegradable films better physical and mechanical qualities than when used alone. Adding gelatin to soy protein films improves their strength and flexibility, because gelatin's linear structure forms a soft, flexible, and elastic gel that provides a less-organized matrix for the complex mixture of mainly globular soy proteins [120]. Gelatin molecules improved the protein chain hydrogen bonding and electrostatic interactions in chicken-feather protein films. Higher gelatin concentrations reduced the film extensibility, such that laminate whey protein films with zein films are used to increase their characteristics. Lamination causes polymer melt-and-flow, creating a homogenous film matrix that increases the tensile characteristics [121]. The development of next-generation polymers necessitates sourcing from renewable materials and a capacity to naturally break down into inorganic molecules. Due to their favorable thermal and mechanical properties, biomass-generation potential, and biodegradability, recombinant structural proteins present promising alternatives to engineered plastics. In this study, the researcher assessed the biodegradability, thermal behavior, and mechanical properties of the BP1(recombinant structural protein). The protein was successfully fashioned into sheets using a manual hot press at 150 °C and 83 MPa. It is noteworthy that thermal deterioration commences beyond 250 °C, and the glass transition temperature is at 185 °C.

The flexural strength and modulus of BP1 were measured at 115 ± 6 MPa and 7.38 ± 0.03 GPa, respectively, surpassing the qualities of commercial biodegradable polymers. The biodegradability of BP1 underwent thorough examination, revealing efficient hydrolysis by isolated bacterial strains in dispersion. Furthermore, three identified proteases effectively hydrolyzed BP1 in its solid state. Mineralization was evaluated through biochemical oxygen demand (BOD)–biodegradation tests with soil inocula. The BOD biodegradability of BP1 reached 70.2 ± 6.0 after 33 days, as reported by Tachibana et al. [122].

5. Applications of Protein-Based Films and Coatings

Protein-based films and coatings have gained significant attention in recent years as sustainable alternatives to conventional plastic packaging materials. Derived from protein sources, like casein, soy, collagen, and agricultural and other byproducts, these biomaterials offer a wide range of applications across different industries (Figures 2 and 3).

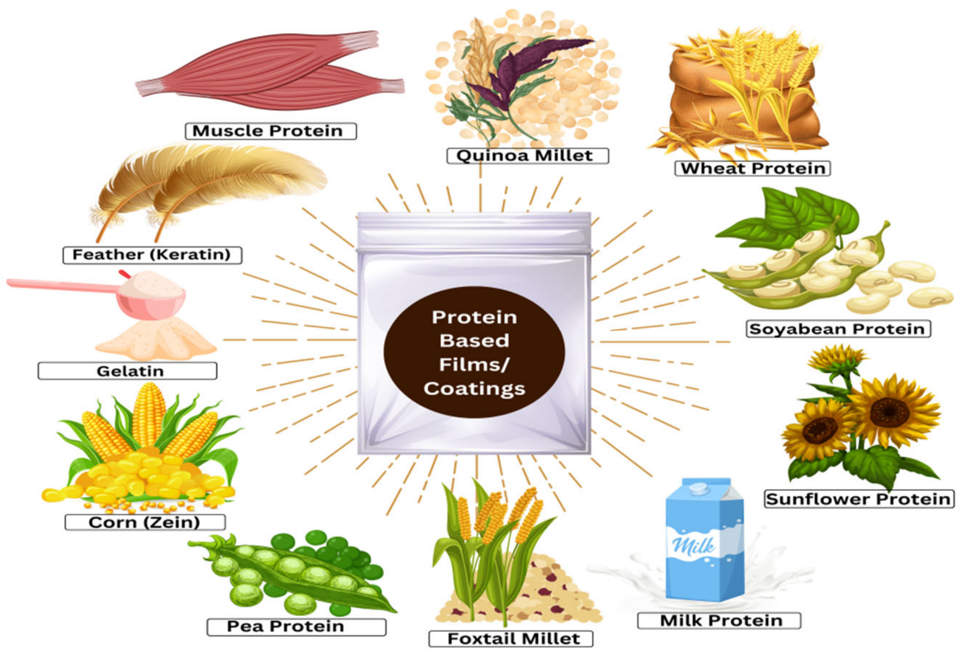

Figure 2. Sources used in the preparation of protein-based films/coatings.

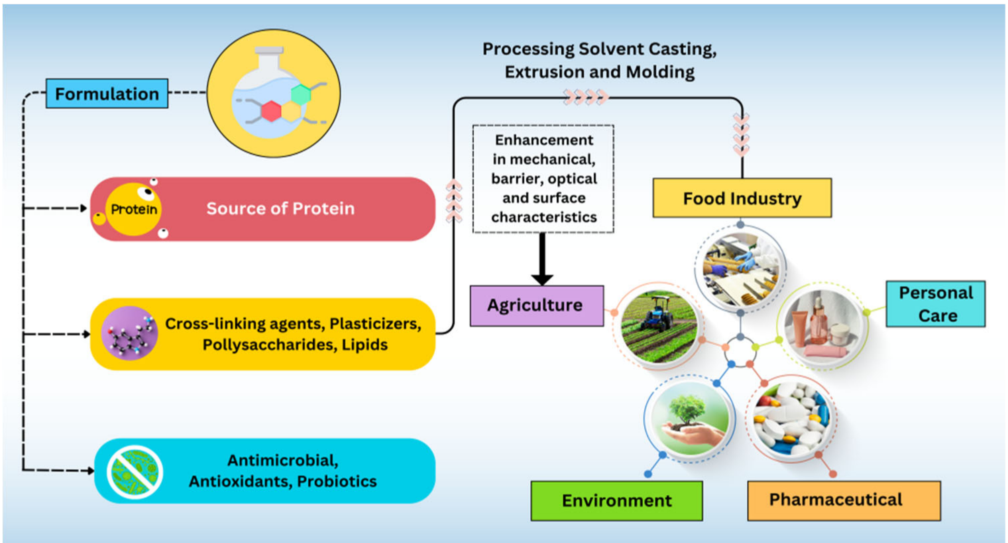

Figure 3. Applications of protein-based films/coatings in different sectors.

5.1. Role in Food Industries

Food packaging plays a crucial role in preserving and protecting the products consumed during our daily routine time. It acts as a bridge between manufacturers and consumers, ensuring the safe delivery of goods. Consumers appreciate packaging that is easy to handle, open, and reseal. Effortless opening mechanisms that eliminate the need for scissors or excessive force are highly valued. The food packaging industry has responded by adopting more ecofriendly practices. Packaging materials derived from renewable resources, such as biodegradable plastics and plant-based materials, are gaining popularity. Additionally, there is a focus on reducing packaging waste by employing minimalistic designs and optimizing material usage. The availability of recyclable and compostable packaging options provides consumers with environmentally responsible choices. These sustainable packaging solutions benefit the planet and resonate with ecoconscious consumers. Packaging must effectively protect the product from contamination, spoilage, and damage during transit. Careful selection of packaging materials ensures they are suitable for specific food products, maintaining their quality and safety. Clear labeling, including accurate information about ingredients, nutritional values, and allergen warnings, is essential for consumer transparency and safety. Functional packaging also considers the needs of diverse consumers, such as incorporating features like easy-to-grip handles or large font sizes for readability. Food packaging has evolved to meet the changing needs and expectations of consumers. Industry's emphasis on ecofriendly practices is highly encouraging, with a move toward more sustainable packaging solutions.

Protein-based films have emerged as an environmentally friendly alternative to traditional plastic packaging [123]. These films offer biodegradability, functionality, and versatility. Each protein source possesses unique characteristics that impacts the film properties, like the strength, barrier performance, and film-forming ability. To enhance the film properties and functionality, modifications and additives can be incorporated during preparation [124]. These may include plasticizers for improved flexibility, cross-linking agents for enhanced mechanical strength, and bioactive compounds for antimicrobial or antioxidant properties. Such modifications expand the potential applications of protein-based films, including controlled-release systems and active packaging. Protein-based films undergo comprehensive characterization to assess their physical, mechanical, and barrier properties. Parameters, like tensile strength, elongation at break, water vapor permeability, and transparency, are evaluated to ensure the compliance with industry requirements.

Coatings and films have found extensive use in the food packaging industry. They offer several advantages, including biodegradability, barrier properties, and preservation capabilities. These films act as edible barriers that protect food products from moisture loss, oxygen exposure, and microbial contamination. They are particularly useful for extending the shelf-life of perishable items, such as fruits, vegetables, meats, and dairy products. Additionally, protein-based coatings can enhance the appearance, texture, and preservation of food items. Protein-based films and coatings act as protective barriers, shielding food products from external factors that can compromise quality and safety. They could also be utilized as a physical barrier against oxygen, moisture, and microbial contamination, helping to increase the shelf-life of perishable food materials [9]. These films help maintain the freshness, texture, flavor, and nutritional value of packaged foods, reducing food waste and improving the overall product quality. Protein-based films and coatings exhibit excellent barrier properties, effectively controlling the exchange of gases, vapors, and aromas between the food and its surrounding environment. They help prevent moisture loss, inhibit oxygen permeation, and reduce the transfer of unwanted odors or flavors. These barrier properties contribute to the preservation of food products, maintaining their sensory attributes and ensuring consumer satisfaction.

5.2. Protein-Based Films/Coatings in Pharma Sector

Protein-based films and coatings exhibit significant potential in the biomedical and pharmaceutical sectors. Their biocompatibility and biodegradability make them well-suited for drug-delivery systems, facilitating the controlled release of therapeutic agents [1,84,125,126]. Applications of these films extend to areas such as wound healing, tissue engineering, and regenerative medicine. They offer the potential to improve the biocompatibility and stability of medical devices and implants when used as coatings. Protein-based films and coatings have emerged as promising carriers for controlled drug delivery [127,128]. They can encapsulate and protect drugs, enabling precise release kinetics and targeted delivery to specific sites in the body. The biocompatibility and biodegradability of protein materials make them ideal for this application, reducing the potential toxicity and minimizing the adverse effects. Coatings and films play a crucial role in wound-healing and tissue-engineering applications. They can serve as scaffolds or substrates to support cell adhesion, proliferation, and tissue regeneration. Protein coatings and their encapsulated forms provide a favorable environment for cell attachment, migration, and differentiation, facilitating the healing process [129–131]. These films can also be tailored to mimic the extracellular matrix, promoting tissue integration and enhancing the overall success of tissue-engineering strategies. Protein-based films and coatings exhibit excellent biocompatibility, making them well-suited for biomedical and pharmaceutical applications. They have a low risk of immune response or rejection when in contact with biological systems. Moreover, protein materials are biodegradable, gradually breaking down and being metabolized by the body over time. This property eliminates the need for surgical removal or implant replacement, reducing patient discomfort and healthcare costs.

Coatings could also be used for medical devices and implants to improve their surface properties and biointegration [132,133]. These coatings improve the biocompatibility of devices, thereby reducing the risk of adverse reactions and fostering tissue integration. They can provide a barrier between the device and the surrounding tissues, preventing adverse effects, such as inflammation or infection. Protein coatings can also be functionalized to immobilize bioactive molecules, such as growth factors or antimicrobial agents, to enhance the device performance and patient outcomes. Films and coatings have been utilized in the development of diagnostic devices and biosensors. These films can immobilize specific antibodies, enzymes, or receptors, allowing for the highly sensitive and selective detection of biomarkers or analytes. The protein coating provides a stable and controlled environment for the recognition elements, ensuring accurate and reliable detection. Protein films also offer excellent signal amplification and signal-to-noise ratios, improving the sensitivity and performance of diagnostic devices. These coatings and films have the potential to encapsulate and stabilize bioactive molecules, such as enzymes, antibodies, or growth factors. This property is particularly valuable for the preservation and controlled release of sensitive biomolecules. Protein films can protect these molecules from degradation, maintain their activity, and control their release kinetics. This enables the development of advanced therapeutic and diagnostic systems with improved stability, efficacy, and shelf-life.

5.3. Personal Care Products

Protein-based films and coatings find applications in personal care products, including cosmetics and toiletries. They are used as encapsulation systems for active ingredients, providing controlled release and improving stability. These films enhance the texture, appearance, and water resistance of cosmetic products, such as lotions, creams, and makeup. Protein coatings can also be utilized to improve the performance and longevity of personal care products. Protein-based films are used for encapsulating active ingredients in personal care products, such as lotions, creams, and serums. These films provide a protective barrier around the active ingredients, preventing their degradation and enhancing their stability. The encapsulated ingredients are released gradually upon application, allowing for controlled release and prolonged efficacy [134,135]. Protein films enable the delivery of key functional compounds, such as antioxidants, vitamins, moisturizers, and antiaging agents, improving the performance and effectiveness of personal care products. Protein-based films can improve the texture and appearance of personal care products. They contribute to the smooth, creamy consistency of creams and lotions, enhancing the sensory experience during application. Protein films can also provide a glossy or matte finish, depending on the desired aesthetic effect. These films improve the overall sensory appeal and consumer experience of personal care products, making them more visually appealing and pleasant to use. Protein-based films are derived from natural sources, making them a desirable option for personal care products marketed as natural or organic. These films are biocompatible, meaning they are well-tolerated by the skin and have a low risk of causing irritation or allergies. Protein-based films provide an alternative to synthetic or chemical-based ingredients, appealing to consumers who prefer more natural formulations. They offer a sustainable and ecofriendly option for personal care products. Films, coatings, or encapsulated forms can be employed for the controlled release of fragrances in personal care products [136–138]. By encapsulating fragrance compounds, these films enable a gradual release of scents, ensuring a longer-lasting effect. Protein films help to maintain the integrity and intensity of fragrances, preventing their rapid evaporation or degradation. This controlled release mechanism enhances the sensory experience of personal care products, providing a pleasing and longer-lasting fragrance.

5.4. Environmental Applications

Coatings and films have potential applications in environmental settings [139–142]. They can be used for soil erosion control, forming a protective barrier on the soil surface to prevent erosion. These films also serve as biodegradable mulch films, reducing weed growth, conserving soil moisture, and enhancing crop yields. Additionally, protein-based coatings can be employed for corrosion protection and the bioremediation of environmental pollutants.

5.5. Biodegradability and Sustainability

One of the key advantages of coatings and films is their biodegradability and ecofriendliness [143–145]. Compared to conventional plastic packaging, which contributes to environmental pollution, protein-based materials offer a sustainable alternative. They can be naturally broken down by microorganisms, minimizing their environmental impact and reducing waste accumulation. This biodegradability aligns with the increasing demand for sustainable packaging solutions and supports a circular economy. Protein-based films and coatings exhibit excellent versatility and compatibility with various food products [84,146]. They can be tailored to specific applications and food types, accommodating different packaging formats and requirements. These materials can be applied to a wide range of products, including fresh produce, meat, dairy, bakery items, snacks, and beverages.

Protein-based films can conform to the shape of the food, providing a customized packaging solution that maintains product integrity. Protein-based films and coatings are often edible, which offers additional benefits in food packaging [1,125,147]. Edible films eliminate the need for package removal before consumption, enhancing the convenience for consumers. Moreover, they can be enriched with functional additives, such as antioxidants, antimicrobial agents, or nutraceuticals. This allows for the creation of active packaging systems that extend the shelf-life, improve food safety, and offer additional health benefits [123,125]. Protein-based films and coatings can enhance the visual appeal of packaged foods. They offer excellent transparency and clarity, allowing consumers to see the product inside. This transparency is particularly beneficial for showcasing the quality, freshness, and attractiveness of food items, boosting consumer trust and purchase decisions. Protein-based films also provide an opportunity for branding and product differentiation through customized packaging designs.

Protein-based films are employed as biodegradable mulch films in agricultural applications. Mulch films are used to cover soil, promoting optimal growing conditions for crops and conserving soil moisture. Conventional plastic mulch films can be difficult to remove after use, leading to environmental issues. Protein-based mulch films, on the other hand, naturally degrade over time, eliminating the need for removal and reducing plastic waste in agricultural fields. Protein-based films and coatings are utilized for soil erosion control in environmental restoration projects. These films can be applied to barren or erodible soils, providing temporary cover and protection. The films help stabilize the soil, reducing water runoff, erosion, and loss of valuable topsoil. Protein coatings support vegetation establishment and growth, facilitating the regeneration of native plant species and promoting ecosystem recovery. Biocompatible films and coatings are employed in the development of biomedical implants [148,149]. These implants can be used in tissue engineering, wound healing, and medical device applications. Protein coatings enhance the integration of implants with surrounding tissues, minimizing adverse reactions and improving patient outcomes. The biodegradability of protein films eliminates the need for implant removal, reducing the potential for additional surgeries and improving the sustainability of medical treatments. Protein-based films and coatings have shown potential for oil spill cleanup and remediation. These films can selectively adsorb hydrocarbons, helping to remove oil pollutants from water surfaces. Bio-based materials can be applied to sorbent materials, such as natural fibers or porous substrates, enhancing their oil absorption capacity and efficiency [150,151]. Protein-based materials offer a sustainable and ecofriendly solution for mitigating the environmental impact of oil spills.

Research endeavors worldwide are pushing the boundaries of protein-based films and coatings across diverse universities. At the University of Massachusetts at Amherst in the United States, there is a focus on developing protein-based films with antifouling properties and drug-eluting capabilities for medical implants. In Saudi Arabia, the College of Applied Medical Sciences at Prince Sattam Bin Abdulaziz University is conducting a comprehensive review of polysaccharides, proteins, and lipid-based natural edible films for food packaging. Meanwhile, at Kansas State University in Manhattan, Kansas, the exploration centers on wheat gluten-based coatings and films, encompassing their preparation, properties, and various applications. Furthering this global trend, the College of Life Sciences and Biotechnology in Korea is actively engaged in the development of protein-based high-oxygen-barrier films using industrial manufacturing facilities. Italy's University of Bologna is focusing on the characterization of composite edible films based on pectin, alginate, and whey protein concentrate. The University of Melbourne in Australia explores the realms of protein adsorption and coordination-based end-tethering of functional polymers on metal–phenolic network films. These instances exemplify a worldwide network of research endeavors, ranging from Brazil to Slovenia, with a focus on diverse applications, like wound dressing, the recyclability of multilayer films, and the physical chemistry study of collagen-based multilayer films. This extensive collaborative effort underscores the global importance of protein-based films and coatings, highlighting their potential applications in various fields, including medicine, food packaging, and materials science. Pertinent work in this domain is detailed in Table 4.

Table 4. The type of work being performed for films of specific purposes.

Place/Country	Type of Work/Purpose	Reference
University of Massachusetts at Amherst, United States	Protein-based films for Medical Implants: Antifouling and Drug-Eluting Antimicrobial Coatings	[152]
College of Applied Medical Sciences, Prince Sattam Bin Abdulaziz University, Al-Kharj, Saudi Arabia	A Review of Natural Edible Films in Food Packaging: Polysaccharide, Protein, and Lipid-Based Approaches	[153]
Kansas State University, Manhattan, Kansas	Coatings and Films Derived from Wheat Gluten: Preparation, Properties, and Applications	[154]
College of Life Sciences and Biotechnology, Korea	Creating High-Oxygen Barrier Films from Proteins in an Industrial Manufacturing Facility	[155]
University of Bologna, Italy	Characterization of Edible Composite Films Comprising Pectin, Alginate, and Whey Protein Concentrate	[156]
The University of Melbourne, Parkville, Australia	Adsorption of Proteins and Coordination-Based End-Tethering of Functional Polymers on Metal-Phenolic Network Films	[157]
Universidade Federal do Rio Grande do Sul (UFRGS), ZC, Brazil	Gelatin-Based Films with Clinoptilolite-Ag for Wound Dressing Applications	[158]
University of Pisa, Via Diotisalvi, Pisa	Recyclability of PET/WPI/PE Multilayer Films through Enzymatic Detergent Removal of Whey Protein Isolate-Based Coatings	[159]
Universidade de Lisboa, Portugal	Innovative Edible Bioactive Films with Melanin-Protein Base for Cheeses: Antimicrobial, Mechanical, and Chemical Characteristics	[160]
University of Brescia, Italy	Impact of Mulching Coatings Based on Hydrolyzed Protein on Soil Properties and Productivity in a Tunnel Greenhouse Crop System	[161]
Universidad Nacional de Colombia sede Medellín, Colombia	Creation and Assessment of Edible Films Derived from Cassava Starch, Whey Protein, and Beeswax	[162]
Université de Strasbourg, CNRS, France	Investigation into the Physical Chemistry of Multilayer Films Based on Collagen	[163]
University of Maribor, Smetanova, Slovenia	Bilayer Coatings Comprising Polysaccharides for Surfaces of Medical Devices with Biofilm-Inhibiting Properties	[164]
University of Massachusetts-Amherst, United States	Chlorinated Protein Films with Biocidal and Antifouling Properties	[165]
University of Auckland, New Zealand	Utilizing Neutron Reflectometry for the Characterization of Surface Coatings with Antimicrobial Proteins	[166]
University of Potsdam, Karl-Liebknecht-Straße, Germany	Moving Towards Protein-Repellent Surface Coatings Utilizing Catechol-Containing Cationic Poly(2-ethyl-2-oxazoline)	[167]
Qilu University of Technology (Shandong Academy of Sciences), Jinan, China	Gelatin-Based Nanocomposite Films Loaded with Silver Nanoparticles for Improved Mechanical Properties and Antibacterial Activity	[168]
Technische Universität MünchenFreising, Germany	Influence of Sodium Sulfite, Sodium Dodecyl Sulfate, and Urea on the Molecular Interactions and Characteristics of Films Based on Whey Protein Isolate	[169]
Headquarters at University of Minho, Avepark, Barco, Portugal	Polysaccharide-Based Multilayered Freestanding Films with Adhesive and Bioactive Elements Fabricated via Spin Coating	[170]

Table 4. *Cont.*

Place/Country	Type of Work/Purpose	Reference
University of Burgundy, France	Significance of Interactions between Coatings Derived from Starch and Plum Fruit Surfaces: A Physical-Chemical Examination	[171]
Universität Bayreuth, Universitätsstraße, Germany	Composite Materials for Drug Delivery Utilizing Engineered Spider Silk Proteins	[172]
Ciudad Universitaria, Córdoba, Argentina	Utilization of Crosslinked Soy Protein Films for Ophthalmic Drug Delivery Applications	[173]
Ludwig-Maximilians-University, Germany	Preparation of Spider Silk Films as Drug Delivery Matrices Using Water-based Methods	[174]
Newcastle University, United Kingdom	Hybrid Polymer Coatings with Marine Antifouling Properties, Formed through Layer-by-Layer Deposition of Polysaccharides and Zwitterionic Silanes	[175]
Purdue University, West Lafayette, Indiana, United States	TEM Grid Coatings Based on Nonfouling NTA-PEG for Selective Capture of Histidine-Tagged Protein Targets from Cell Lysates	[176]
University of Toronto, Canada	Water-Based Production of Low-VOC Nanostructured Block Copolymer Films for Prospective Marine Antifouling Coatings	[177]
Department of Health Sciences and Technology, ETH Zurich, Zurich, 8092, Switzerland	Amyloid Superwetting Films as Functional Coatings	[178]
University of São Paulo, Brazil	Characteristics of Gelatin-Based Films Containing Chitosan-Coated Microparticles Loaded with Rutin	[179]
University of Piraeus, Piraeus, Greece	Optimizing Artificial Chemoreception in Bilayer Lipid Membranes Using Protein-Based Graphene Biosensors	[180]
University of Wollongong, NSW 2500, Australia	Polypyrrole Films with Conductive and Protein-Resistant Properties for the Delivery of Dexamethasone	[181]
University of Life Sciences-SGGW (WULS-SGGW), Poland	Moisture Sensitivity, Optical, Mechanical, and Structural Characteristics of Edible Films Based on Whey Protein Incorporating Rapeseed Oil	[182]
Universidad Autónoma de Querétaro, Querétaro 76010, Mexico	Enhancing the Characteristics of Thin Films Based on Amaranth Protein Isolate for Food Packaging Applications: Nano-Layering through Spin-Coating and Integration of Cellulose Nanocrystals	[183]
University of Technology (Shandong Academy of Sciences), Jinan, China	Formulation and Physicochemical Characteristics of Intelligent Edible Films Derived from Gelatin-Starch Nanoparticles	[184]
Universidad Veracruzana, Av. Doctor Luis Castelazo, Industrial Las Animas, Xalapa Enríquez C.P. 91190, VER, Mexico	Utilizing Cocoa Nanoparticles to Enhance the Physicochemical and Functional Attributes of Whey Protein-Based Films for Prolonging the Shelf Life of Muffins	[185]
Protip Medical, 8 Place de l'Hôpital, 67000 Strasbourg, France	Versatile Polymeric Coatings for Implants Incorporating Gelatin, Hyaluronic Acid Derivative, and Chain Length-Controlled Poly(Arginine)	[186]

6. Conclusions

Protein-based films and coatings offer a sustainable and versatile solution for various industries. Their diverse applications in food packaging, biomedical and pharmaceutical fields, agriculture, personal care products, environmental settings, and smart packaging demonstrate their potential to revolutionize multiple sectors. Ongoing research and development efforts continue to enhance the properties, functionality, and application potential of edible coatings and films, further solidifying their position as an environmentally friendly alternative to conventional packaging materials.

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