Food Hydrocolloids for Health 6 (2024) 100182

Contents lists available at ScienceDirect

Food Hydrocolloids for Health

journal homepage: www.elsevier.com/locate/fhfh

Investigating next-generation edible packaging: Protein-based films and coatings for delivering active compounds

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A R T I C L E I N F O

Keywords:
Protein films
Probiotics
Prebiotics
Active packaging

A B S T R A C T

Edible film and coating are nutritious and beneficial for the host as those are consumed with food. Among various edible films and coatings, this review focused on protein-based films and coatings due to their potential application as a carrier for bioactive compounds in the food and biomedical industries. Bioactive compounds such as probiotics, prebiotics, and phenolic compounds have shown promise in maintaining intestinal health. They enhance immune response, lower inflammation in gastrointestinal illnesses, and help to prevent colon cancer. However, these bioactive compounds are often susceptible to environmental factors such as temperature, oxygen, pH etc. Consequently, encapsulation of these compounds becomes essential to protect them from potential damage and ensure the delivery of these compounds into the host body while retaining their intended functional properties. Current trends involve incorporating phenolic compounds into films or encapsulating probiotics and prebiotics as core materials using different wall materials. These encapsulated compounds can be intake with the food. Ongoing research endeavors are dedicated to improve the mechanical properties or functional properties of edible films and coatings separately. This review aims to overcome existing limitations of encapsulation of bioactive compounds into various types of protein film and enhance the functionality and health benefits and unlock the application of protein-based edible films and coating in the food industry.

Introduction

Edible films are generally used to encase a food product, and coatings are directly applied to the food. Films are materials with a thickness between 0.050 and 0.300 mm, and coatings are below 0.025 mm (Ceylan & Atasoy, 2023; Gupta, Biswas, & Roy, 2022). Recently, consumers have become increasingly interested in adopting edible films and coatings as an alternative to plastic packaging due to concerns arising from the environmental impact of plastic and the challenges associated with reducing its usage in processed foods and fresh agricultural products (Tavassoli-Kafrani, Gamage, Dumée, Kong, & Zhao, 2022). These films and coatings are able to prevent water vapor transfer, prolong the duration of storage, and provide the foods with an acceptable color, aroma, taste, and texture (Bizymis & Tzia, 2022; Ulusoy, Yildirim, & Hecer, 2018). In this context, edible protein films and coatings have received attention since being classified as Generally Recognized as Safe (GRAS) by the US Food and Drug Administration (Shahidi & Hossain, 2022). Edible films and coatings can be fabricated from proteins, polysaccharides (starch, alginate, pectin, chitosan, and cellulose derivatives), lipids (wax, fatty acids, and acylglycerols), or a combination thereof. Both hydrocolloids (proteins and/or polysaccharides) and lipid molecules (Kandasamy, et al., 2021; Ramos, Fernandes, Silva, Pintado,

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https://doi.org/10.1016/j.fhfh.2024.100182
Received 31 October 2023; Received in revised form 1 June 2024; Accepted 17 June 2024
Available online 17 June 2024

& Malcata, 2012; Rossi-Márquez, Dávalos-Saucedo, & Di Pierro, 2023; Shahidi & Hossain, 2022) are encapsulated within compound film structures.

Protein-based materials seem more appealing than other edible film sources since the tensile strength of protein films (e.g. gelatin film 68 MPa) are higher than polysaccharides films e.g. chitosan films 41 MPa) (Moreno-Ricardo, Gómez-Contreras, González-Delgado, Hernández-Fernández, & Ortega-Toro, 2024). The edible films and coatings market is likely to rise to USD 3.2 billion in 2023, and the market is estimated to reach USD 3.46 billion with a CAGR of 8.3% by (The Business Research, 2024). Protein can be extracted from plants, animals, and marine biota (Arnon-Rips & Poverenov, 2016; Cahyana, et al., 2023). Proteins used for films and coatings include soy protein, whey protein/milk protein, wheat gluten protein, sodium caseinate, corn zein, gelatin and collagen, peanut protein and protein isolate, sesame protein isolate, myofibrillar proteins of fish muscle, lentil protein, pumpkin seed protein, egg white protein and rice protein etc. (V, et al., 2022). Moreover, the well organized hydrogen-bonded structure makes protein-based edible films have considerably higher barrier capabilities than those derived from lipids and polysaccharides. However, they have lower moisture barrier properties, limiting their use for certain applications (V, et al., 2022). Protein coatings are hydrophilic, capable of imbibing moisture, and chemically modifiable to alter their properties (Hassan, Chatha, Hussain, Zia, & Akhtar, 2018; Ribeiro, Estevinho, & Rocha, 2021).

Edible films and coatings could be encapsulated with vitamins, minerals, and other nutrients that are controlled and slowly released (Chaudhary, Thakur, Kajla, Thakur, & Punia, 2021) and can increase the nutritional status (Guan, et al., 2022; C. Wen, Zhang, Zhang, & Duan, 2022) of foods as it is ingested. Moreover, they are able to carry bioactive compounds (probiotics, phenolics, antimicrobials, anti-oxidants, nutraceuticals, anti-browning agents, flavor, aroma, color, etc.) (Chawla, Sivakumar, & Kaur, 2021; R. K. Deshmukh & Gaikwad, 2022; Hamed, Jakobsen, & Lerfall, 2022; Nehra, Biswas, Siracusa, & Roy, 2023; V, et al., 2022; Xie, et al., 2022) which boost the bioavailability and assimilation of these nutrients (P. Wen, Zong, Linhardt, Feng, & Wu, 2017) and provide health benefits (Matsuoka & Sugano, 2022). Bioactive compounds are often encapsulated where protein is used as a wall material to protect them from environmental factors (pH, temperature) during processing, as well as after consumption.

Films and coatings can be fabricated and encapsulate bioactive compounds into them by several methods. The five most common methods for applying edible films and coatings to food products are dipping, brushing, spraying, solvent casting, and extrusion (Ulusoy, et al., 2018). These methods could be modified to compose different wall materials, as well as optimize the process parameters according to the optimal conditions of bioactive compounds.

This review aims to comprehensively summarize recent advancements in utilizing protein for the development of edible films and coatings, with a focus on achieving desired characteristics and features. Various sources of protein and the properties of fabricated films and coatings will be reviewed. Additionally, it explores the integration of different probiotics, prebiotics, and phenolic compounds into these edible films and coatings. Furthermore, the progress of different encapsulation methods, their possibilities and limitations have been highlighted.

Protein-based films and coatings

Proteins consist of different monomers, which makes them unique in structure and confers a variety of functional characteristics. Proteins are better at getting desirable coating or packaging applications than polysaccharides and lipids due to their strong capacity for intermolecular interaction. Several applications of edible protein films and coatings are seen in foods, for instance, fish and seafood, meat and meat-related products, fruits and vegetables (Jafarzadeh, Forough, et al., 2022; Zhen, et al., 2022), bakery products (cookies, bread, snacks), beverages (Jaeger, Zannini, Sahin, & Arendt, 2021), dairy products and frozen foods (Chen, et al., 2019), cereal grains and nuts (Jafarzadeh, Hadidi, Forough, Nafchi, & Mousavi Khaneghah, 2022). Protein-based edible films and coatings can be classified into two broad groups, which are plant and animal protein, depending on the source of origin. Protein properties like solubility, molecular weight, and isoelectric point (IP) are crucial factors in the fabrication of films and coatings. Proteins obtained from plant and animal origin have been reviewed in this section and summarized the matrix polymer, additives, characteristics, and application in Table 1.

Plant protein film

Plant-based proteins serve vital functions in food formulations due to their water/oil-binding, foaming, gelling, thickening, and emulsifying properties. In addition, they also have biological roles like antioxidant, antifungal, and antibacterial activity (M. Kumar, et al., 2021). Plant-protein-based films and coatings have different functionality, structure, and composition, causing them to manifest a series of desirable thermal, mechanical, barrier, and sensory properties (Milani & Tirgarian, 2020). Gluten, soy proteins, zein, pea proteins and sunflower seed proteins are the most common used ones in the fabrication of protein films and coatings among plant proteins (Hadidi, et al., 2022).

Wheat gluten protein

The wheat kernel is composed of 12-16% protein, which is known as wheat gluten protein, remain 75-80% protein after washing the wheat flour (Chavoshizadeh, Pirsa, & Mohtarami, 2020). Monomer gliadins (28-55 kDa) and polymer glutenins (500-10000 kDa) make up most of wheat gluten protein and are equally distributed by weight. The IP of wheat gluten is less than pH 5.5. The intermolecular-disulfide interactions in glutens facilitate cohesiveness and elasticity characteristics, which provide film-forming properties (Fakhouri, et al., 2018). Wheat gluten film possesses excellent carbon dioxide and oxygen barriers but poor water vapor barrier properties (García Ibarra, Sendón, & Rodríguez-Bernaldo de Quirós, 2016). Wheat gluten is the suggested source of protein for edible packaging because of its availability, low cost, low water solubility, ability to form cross-links when heated, viscoelasticity, and other features (Ansorena, Zubeldía, & Marcovich, 2016). The mechanical characteristics of manufactured films are affected by the pH and gluten content, while the water vapor permeability is associated with the pH of film forming solution and percentage of ethanol (Fakhouri, et al., 2018). Other proteins, polysaccharides, and organic acids can be added to wheat gluten films to enhance their physiochemical characteristics (Dong, et al., 2022; He, Wang, Feng, Chen, & Wang, 2020).

Soy protein isolate (SPI)

Soybeans are composed of 35-40% protein which is mainly water soluble albumins and salt soluble globulins (Qin, Wang, & Luo, 2022). Soy protein is isolated from soybeans through dehulling, flaking, and defatting with a protein content of over 90% (Kutzli, Weiss, & Gibis, 2021). Globulin, the primary protein, consists of 30% glycinin (11S) and 40% β-conglycinin (βCG, 7S) (Sui, Zhang, & Jiang, 2021). The IP of SPI is at pH 4-5. The structural features of natural soy protein make it difficult to use in applications like edible packaging. The properties could be improved by reinforcing with nanofibers or nanocrystals (González, Gastelú, Barrera, Ribotta, & Álvarez Igarzabal, 2019). Moreover, it is possible to alter soy protein by cross-linking the protein structure using a variety of techniques, including denaturation, heat treatment, and cross-linking agents (Xia, et al., 2015). The flexibility, oxygen barrier property, optical transparency, wide availability and inexpensive are the main characteristics of SPI-based edible films (Nandane & Jain, 2018). The SPI's gelling properties make it simple to create a useful matrix for composite films and bioactive substances such as antioxidants and

Table 1
Edible films and coatings fabricated by different protein

Matrix polymer	Additives	Observations	Application	References
Wheat gluten protein	Egg white protein, pectin, Tartaric acid	Enhanced thermal stability, physical strength, and UV resistance	Edible film	Dong et al. (2022)
	Glycerol	Improved the strength, stiffness, and extensibility	Edible film	Rasheed, Plivelic, Kuktaite, Hedenqvist, and Johansson (2018)
	Urea	Improved the barrier and mechanical properties	nanocomposite	Kuktaite, Türe, Hedenqvist, Gällstedt, and Plivelic (2014)
	Beeswax	Decreased the tensile strength	Edible film	Duan et al. (2023)
Soy protein	Cellulose nanocrystal	Improved the mechanical property		Yu et al. (2018)
	Cellulose nanofiber	Improved the mechanical property but decreased the susceptibility to water		González et al. (2019)
	Rapeseed oil	Reduced the water vapor permeability, tensile strength, and contact angle		Galus (2018)
	Beeswax	Increased thermal stability	Edible film	Duan et al. (2023)
Corn zein	Sunflower oil	Decreased the water vapor permeability and sorption behavior	Edible film	Mouzakitis et al. (2022)
	Beeswax	Decreased the thermal stability, changed the opacity	Edible film	Duan et al. (2023)
	Catechin/cyclodextrin	Elevated the mechanical and barrier properties	Edible film	Jiang et al. (2023)
	Chitosan, cinnamaldehyde, nano-cellulose	Improved the water resistance, microstructure, and chemical structure	Edible film	Xiao et al. (2021)
Pea protein	Pullulan	Improved the mechanical and water-resistance properties	Edible film	J. Cheng, Wang, Li, Chen, and Cui (2023)
	Glycerol	Improved the tensile strength and elongation at break	Edible film	Cheng et al. (2022)
	Cassava starch	Enhanced the barrier properties	Edible film	Huntrakul et al. (2020)
	Haskap leaf extracts	Improved the barrier properties	Films and coatings	Chong and Brooks (2022)
Whey protein isolate	TiO_2 nanotubes	Increased antioxidant activity	Coating	Feng et al. (2019)
	Glycerol, trehalose	Enhanced the hydrophobic and antioxidant activity	Edible coating	Feng et al. (2018)
	Cassava starch, rambutan peel extract, cinnamon oil	Reduced microbial growth	Edible film	Chollakup et al. (2020)
Sodium caseinate	Gallic acid, rosemary oil	Improved the antioxidant property	Coating	Valentino, Volpe, Di Giuseppe, Cavella, and Torrieri (2020)
	White tea extract	Enhanced the puncture strength, thermal stability, and water vapor permeability	Edible film	Pluta-Kubica, Jamróz, Kawecka, Juszczak, & Krzyściak (2020)
	Oregano oil, garlic oil, Nisin, Natamycin	Improved the antimicrobial activity	Edible film	Seydim et al. (2020)
	Chitosan and Oregano Essential Oil	Improved the barrier properties	Coating	Ríos-de-Benito et al. (2021)
	Arabic gum, essential oil of cinnamon and lemon grass	Slower the firmness and sugar contents	Coating	Murmu and Mishra (2018)
Collagen and gelatin	orange peel extract	Slightly modified the mechanical and thermal properties	Edible film	Jridi et al. (2019)
	Orange leaf essential oil	Inhibited the formation of melanosis	Coating	Alparslan et al. (2016)
	Chitosan, clove and pepper essential oils	Improved the mechanical and barrier properties	Coating	Shakila, Jeevithan, Arumugam, and Jeyasekaran (2016)
Myofibrillar proteins	Chitosan, rosemary extract	Enhanced the mechanical properties	Edible film	Du et al. (2021)
	Nanocrystalline cellulose, anthocyanins	Improved the mechanical and barrier properties	Edible film	J. Chen et al. (2023)
	Grape seed procyanidins, green tea polyphenol	Improved the rigidity and thermal stability	Edible film	Nie, Gong, Wang, and Meng (2015)
Egg white protein (EWP)		Improved the water-resistant, mechanical and heat properties	Edible film	Deng, Xu, Hu, and Sheng (2022)

antibacterial agents (de Souza, et al., 2020). However, the inherent hydrophilicity and strong molecular interactions of natural soy protein result in poor film-forming properties, mechanical performance, and toughness of the resultant films (Felix, Martinez, Romero, Partal, & Guerrero, 2018; Liu, Wang, Zhang, Zhang, & Li, 2019), which considerably limit the application of soy protein-based films.

Corn zein

Corn is composed of 6-12% protein on a dry basis, of which 45-50% is zein (Shukla & Cheryan, 2001). Corn proteins are classified into albumin, globulin, glutelin, and zein, which are soluble in water, salt, alkali, and alcohol, accordingly (Reineccius & Meng, 2023). The IP of zein is pH 6.4. It consists of α-zein, β-zein, γ-zein, and δ-zein. Zein is used to make edible pouches, coatings, and films (Zhang & Zhao, 2017). The hydrophilic and hydrophobic domains on the surface of zein made it possible to self-assemble. Zein could be used as a coating to improve the barrier property through the protein-protein interaction of hydrophilic protein-based film. Zein was an edible film matrix material because of the residues of non-polar amino acids that were present in it. Zein was studied for the fabrication of composite film with protein (SPI, gelatin) and polysaccharide (glucomannan) (Wang, et al., 2017). Zein is a useful matrix for the creation of nanoparticles that can encapsulate a variety of bioactive substances, improve their stability during processing and storage conditions, and increase their bioavailability in artificial gastrointestinal systems that imitate human ingestion (Sharif, Fabra, & López-Rubio, 2019). However, the lack of mechanical robustness and low thermal stability of zein impose a major limitation on their direct usage as packaging materials (Tadele, Trinh, & Mekonnen, 2023).

Pea protein

Pea seeds are composed of 20-30% protein, which are mainly globulins (65-80%) and albumins (10-20%). The globulins present in the pea protein are legumin 11S (300-400 kDa), vicilin 7S (150–170 kDa) and conviction 7S (70 kDa), which are salt-soluble storage proteins (Bogahawaththa, Bao Chau, Trivedi, Dissanayake, & Vasiljevic, 2019). Albumins 2S (5-80 kDa) are metabolic proteins that are soluble in water and can be classified into enzymes, enzyme inhibitors and lectins. The IP of pea protein is pH 4-5 (Cui, et al., 2020). Pea protein isolate has been reported to fabricate film and coating (Chong & Brooks, 2022). Plasticizer, cross-linker and bioactive compounds were incorporated to improve the physical, mechanical and functional properties of the film (Chong, Yuryev, Jain, Mason, & Brooks, 2021). Pea protein has been reported for several health benefits, including antihypertensive, antioxidant, regulating the activity of bacteria in the gut, as well as improved emulsifying, gelling, foaming and oil/water holding capacities (Ge, et al., 2020). The poor flexibility of pea proteins limits their application as a pure compound in film processes (Huntrakul, Yoksan, Sane, & Harnkarnsujarit, 2020).

Sunflower seed protein

Sunflower seeds consist of 30-50% protein, which are mainly sunflower albumins (25-30%) and globulins (60-80%). The salt soluble globulins present in sunflower seeds are helianthinin 11S (300-350 kDa), which can split into monomers (2S-3S) or oligomers (7S). Sunflower albumins (16 kDa) are water soluble storage proteins. The IP of helianthinins has been reported in the pH range of 4 to 6, while sunflower albumins have an IP of around 9 (Sara, et al., 2020). Sunflower protein isolates have been reported to fabricate biodegradable film by extrusion (Rouilly, Mériaux, Geneau, Silvestre, & Rigal, 2006). It has also been suggested that sunflower meal proteins are suitable building blocks for food-grade films incorporating anti-oxidants and antibacterial ingredients, including essential oils, protein hydrolysates, and grapefruit seed extract (Kaur & Ghoshal, 2022). The tensile strength of sunflower seed protein films (3.5 – 5 MPa) (Salgado, Molina Ortiz, Petruccelli, & Mauri, 2010) is lower than low-density polyethylene (4.1 -15.9 MPa) (Dilara & Briassoulis, 2000; Rennert, et al., 2013) which limits its application.

Animal protein film

Animal protein shows excellent optical transparency, tensile strength and gas barrier properties. Animal proteins that are widely used film and coating are whey protein, casein, gelatin, myofibrillar proteins, and egg proteins (Davidov-Pardo, Joye, & McClements, 2015).

Whey protein isolate

Whey protein isolate (WPI), containing over 90% protein, is a co-product of cheese. The α- and β -lactoglobulin consist of the major portion and determine the functional properties of WPI. The IP of whey proteins is less than pH 5.5, and sweet whey is pH 6.1 (Durham & Hourigan, 2007). By mixing various emulsifiers and plasticizers with whey protein fraction, WPI, and whey protein concentrate (WPC), edible films can be prepared (Çakmak, Özselek, Turan, Fıratlıgil, & Karbancioğlu-Güler, 2020; Seydim, Sarikus-Tutal, & Sogut, 2020). The advantage of using whey protein or casein over total milk protein for film preparation is that the crystallization could be avoided due to the absence of lactose (Wagh, Pushpadass, Emerald, & Nath, 2014). The whey protein film showed excellent barrier properties against oxygen, aroma, and oil when the humidity was medium or low. The sufficient mechanical properties enhanced the application of the film for food coating, separating layers, and pouch formation. Probiotics and prebiotics have recently been added to whey protein-based films to improve their functional qualities (Fernandes, Guimarães, Pimentel, et al., 2020; Zoghi, Khosravi-Darani, & Mohammadi, 2020). Among other advantages, whey-derived bioactive components have antimicrobial and antiviral properties, improve immune function and bone health, increase antioxidative activity, aid in the prevention of cancer and cardiovascular disease, and improve the performance of those who engage in physical activity (León-López, et al., 2022).

Sodium caseinate

Casein can be converted to sodium caseinate (SC), a water-soluble form, by correcting acid-coagulated casein to pH 6.7 with sodium hydroxide. The presence of random coils in the structure of the SC facilitates good film formation (Lin, Wang and Weng, 2020). The barrier properties of SC film could be improved by modifying the surface of the film with zein coating. Recent research has shown that adding essential oils and antimicrobial compounds (Alizadeh-Sani, Rhim, Azizi-Lalabadi, Hemmati-Dinarvand, & Ehsani, 2020; Di Giuseppe, Volpe, Cavella, Masi, & Torrieri, 2022), as well as cross-linking with genipinin (Lin, et al., 2020; Qiu, Wang, & Weng, 2020), improve the mechanical and antibacterial capabilities of SC films.

Collagen and gelatin

Collagen makes up about 30% of the animal protein, which has a molecular weight of about 100 kDa and is made up of three α-chains with a total of about 1,000 amino acids in each. Collagen swells in polar liquids with high solubility parameters used in edible packaging. It is a hydrophilic protein rich in glycine, hydroxyproline, and proline (Coppola, et al., 2020). The collagen present in animal bone and skin could be denatured by thermal treatment in the presence of dilute acid to prepare gelatin (López, et al., 2017).

Gelatin is a protein made from collagen by carefully regulated hydrolysis. The biopolymer gelatin consists of glycine, proline, and 4-hydroxy proline residues (Deshmukh, et al., 2017). Two different forms of gelatin can be produced from native collagen depending on whether acidic or alkaline pretreatments are used during the gelatinization process: categories A and B (Mohiti-Asli & Loboa, 2016). Gelatin is well known for having a wide range of uses due to its high gas and oil resistance, strong film-forming ability, nontoxicity, low cost, and biodegradable characteristics. In numerous research investigations, the use of gelatin as an edible film has been thoroughly investigated (Cui, Cheng, Li, Khin, & Lin, 2023; Jridi, et al., 2019). Gelatin can fabricate films with good mechanical properties; however, the high-water solubility, low thermal stability and ductility limits the application of gelatin film. The limitations of gelatin films could be overcome by fabricating composite film utilizing starch or zein (Ahammed, Liu, Khin, Yokoyama, & Zhong, 2020; Cheng, Gao, Wang, Hou, & Lim, 2022). Collagen has a long story of usage as a casing for meat products (Yang, Wang, Wang, & Luo, 2016).

Myofibrillar proteins

Myofibrillar proteins, the main proteins in muscles, make up about 66%–77% of the total fish muscle and approximately 55%–65% of the total meat muscles (Dara, et al., 2021). The IP of myofibrillar protein is pH 5.5 (Chen, Tume, Xu, & Zhou, 2017). Myofibrillar proteins from several animals have been used to create edible protein films. However, most research has concentrated on fish as the primary source of protein. The likelihood of intermolecular interactions forming is mostly influenced by the protein structure (globular or fibrous) and the physicochemical conditions during processing. Myosin and other high molecular weight and fibrous proteins can typically form films with good mechanical properties. Still, globular or pseudo-globular proteins, such as G-actin, must first be unfolded before film production (Chen, Qiu, Chen, Li, & Liang, 2020).

Egg white protein (EWP)

The main ingredients in egg whites are protein (11%–13%) and water (Jin, Chen, Zhang, & Sheng, 2021). The egg white protein is soluble in saline, and the IP is at pH 4.5 (Razi, Fahim, Amirabadi, & Rashidinejad, 2023). Ovalbumine (54%), ovotransferrin (12%), and ovomucoid (11%) are the main globular proteins present in EWP. However, lysozyme contains S-S bonds, which are converted to S-H groups at pH ranges from 10 to 12 and form inter- and intramolecular S-S covalent cross-linking during the heating treatment. The mechanical and gas barrier properties of egg white edible film can be improved by crosslinking with ultraviolet light treatment. The use of egg white in film and coating production represents a nutritional interest since it is an effective antioxidant. Egg whites are high in pure protein and increase muscle mass and strength enhancement, lowering cholesterol and visceral fat reduction (Matsuoka and Sugano, 2022).

Bioactive compounds

Bioactive compounds are derived from various flora and fauna (Subramanian & Anandharamakrishnan, 2023). Comprehending the variables that affect the stability and delivery of these substances is crucial for their advancement. The beneficial effects of biologically active compounds may be reduced due to their malfunction or degradation, causing a decline in their claimed health advantages. Furthermore, the physiological impacts of these compounds are executed through complex mechanisms that entail interactions with cellular constituents and molecular receptors (Serrano, Jove, Gonzalo, Pamplona, & Portero-Otin, 2015). The characteristics and application of different bioactive compounds, such as probiotics, prebiotics, and phenolic compounds incorporated in edible films and coatings, have been discussed in this section and summarized in Table 2.

Probiotics

Probiotics are defined as live microorganisms that, when administered in adequate amounts, confer a health benefit on the host (Gibson, et al., 2017). By contrast, prebiotics, a substrate that is selectively utilized by host microorganisms conferring a health benefit (FAO, 2006). In the modern era, the domains of science, medicine, and people have recently witnessed a surge in attention towards probiotics and prebiotics. The recognition and significance of health-promoting microorganisms impact the development of the probiotic sector. The global prebiotics market size was valued at USD 6.05 billion in 2021 and is expected to grow at a compound annual growth rate (CAGR) of 14.9% from 2022 to 2030 according to the Grand View Research (G. V. Research, 2020).

Lactobacillus plantarum has proven to be a valuable species for the development of probiotics, with various beneficial effects on gut health, metabolic disorders, and brain health (Y. W. Liu, Liong, & Tsai, 2018). Edible film of whey protein and gelatin incorporated with *L. plantarum* for the food industry to coat different foodstuffs to obtain functional products (Sáez-Orviz, Marcet, Rendueles, & Díaz, 2022). ***Lactobacillus casei*** enhances brain function, barrier function, immune modulation, pathogen resistance, and anti-cancer activity (Hill, et al., 2018). *L. casei* is incorporated in WPI edible biofilm for packing formulated with

Table 2
Examples of bioactive compounds incorporated in the different edible films and coatings.

Bioactive compounds	co-components	Application	Reference
Probiotics			
Lactobacillus plantarum		Whey and gelatin edible film	Sáez-Orviz et al. (2022)
Lactobacillus casei		Whey protein isolate	Dianina et al. (2019)
Lactobacillus paracasei, Kluyveromyces marxianus		Whey proteins and polysaccharide kefiran edible film	Gagliarini et al. (2019)
Lactobacillus acidophilus Bifidobacterium bifidum		Gelatin edible coatings and films	López de Lacey et al. (2012)
Bifidobacterium animalis, Lactobacillus casei	Glycerol	Whey protein isolate edible film	Odila Pereira et al. (2016)
Prebiotics			
	Galactooligosaccharide and Xylooligosaccharide	Whey protein film	Fernandes et al. (2020)
	Fructooligosaccharides	Methylcellulose-based films	Romano et al. (2014)
	Fructooligosaccharides	Cassava starch edible films	Bersaneti et al. (2016)
	Xylooligosaccharides	Hemicelluloses/chitosan-based films	Xu et al. (2019)
	Pectin	Casein, egg albumin edible film	Sood and Saini (2022)
Synbiotics			
Lactobacillus plantarum	Polydextrose	Whey protein isolate film	Karimi, Alizadeh, Almasi, and Hanifian (2020)
Lactobacillus delbrueckii, Lactobacillus plantarum	Fructooligosaccharides	Methylcellulose-based films	Romano et al. (2014)
Lactobacillus rhamnosus	Fructooligosaccharides	Alginate edible coating	Bambace, Alvarez, and Moreira (2019)
Bixa orellana L.	Inulin	Whey protein isolate, gum acacia, starch	Silva, Zabot, Cazarin, Maróstica, and Meireles (2016)
Lactobacillus rhamnosus	Inulin, polydextrose, glucose-oligosaccharides and wheat dextrin	Gelatin edible film	Soukoulis, Behboudi-Jobbehdar, Yonekura, Parmenter, and Fisk (2014)
Lactobacillus casei	Inulin	Starch films	Orozco-Parra, Mejía, and Villa (2020)
Bifidobacterium animalis	Inulin and fructooligosaccharides	Whey protein isolate and alginate edible film	Odila Pereira et al. (2019)
Lactobacillus acidophilus	Mannitol, locust bean gum	Coating	Yee, Yee, Lin, and Phing (2019)
Lactobacillus plantarum	Fructooligosaccharides	Methylcellulose edible coating	Tavera-Quiroz et al. (2015)
Lactobacillus rhamnosus	Sodium caseinate, soy protein concentrate, bovine skin gelatine caseinate	Corn and rice starch edible film	Soukoulis, Singh, Macnaughtan, Parmenter, and Fisk (2016)
Lactobacillus rhamnosus	Citric acid	Sodium carboxymethyl cellulose and hydroxyethyl cellulose	P. Singh et al. (2019)
Phenolic compounds			
Gallic acid		Carboxymethyl cellulose and whey protein concentrate edible coating.	Hosseini et al. (2020)
Anthocyanin		Corn starch bioactive film	Ribeiro Sanches et al. (2021)
Catechin, Epicatechin gallate		Chitosan edible coating	Sabaghi, Maghsoudlou, Khomeiri, and Ziaiifar (2015)
Hydroxytyrosol (HT), 3,4-dihydroxy-phenylglycol (DHPG)		Pectin-gelatin edible bioactive film	N. Kumar et al. (2021)

tomatoes and grapes (Dianina, Jrb, Pimentelc, Hernandesa, & Costaa, 2019). ***Lactobacillus acidophilus*** can help manage diarrhea and gastrointestinal diseases, boost immune system function, alleviate allergy symptoms, and treat and prevent vaginal infections. It has been incorporated in gelatin edible coatings and films (López de Lacey, López-Caballero, Gómez-Estaca, Gómez-Guillén, & Montero, 2012). ***Bifidobacterium animalis***: *B. animalis* and *B. lactis* were formerly recognized as discrete microbial species. At present, both variants are classified as *B. animalis*, comprising the subspecies *B. animalis* and *B. lactis*. Incorporation of *B. animalis* subspecies *lactis* BB-12 was observed in the WPI edible film (Odila Pereira, et al., 2019).

The strength and water solubility of the edible films were affected by the presence of lactobionic acid, and though all these films were homogeneous, they were slightly opaque (Sáez-Orviz, et al., 2022). The WPI film containing probiotic culture was yellowish, thicker (16.18 vs 13.15 μm), more soluble in water (42.8 vs 34.8%), had higher resistance (higher tensile strength, 23.3 vs 12.6 N) and was less flexible (lower elongation at break, 5.27 vs 45.4%) compared to the WPI film without probiotic (Dianina, et al., 2019). The whey protein-kefiran film matrix showed good capability protecting the included probiotics from stress during film obtaining process and through gastrointestinal passage simulation (Gagliarini, Diosma, Garrote, Abraham, & Piermaria, 2019).

Prebiotics

Carbohydrates, particularly dietary fiber, constitute the majority of prebiotics that have been identified. The utilization of lactulose, a partially synthetic disaccharide, has been established as a means for alleviating constipation and has been noticeably validated to possess prebiotic properties (Senés-Guerrero, Gradilla-Hernández, García-Gamboa, & García-Cayuela, 2020). **Galactooligosaccharides (GOS)** consumption has been shown to enhance mineral absorption, boost the immune system, induce a sensation of satiety, mitigate the risk of allergies, and promote the proliferation and metabolic function of both lactobacilli and bifidobacterial in the colon (Souza, Gabardo, & Coelho, 2022). **Fructooligosaccharides (FOS)** consumption may result in reduced concentrations of serum cholesterol, phospholipids, and triacylglycerols, as well as increased mineral assimilation and a low risk of oncogenicity (Kumar, Sripada, & Poornachandra, 2018). **Xylooligosaccharides (XOS)** exhibit anti-inflammatory, antioxidative, tumor-suppressive, and antimicrobial properties (Althubiani, et al., 2019). **Isomaltooligosaccharides (IMOs)** is attributed to their high digestibility in the gastrointestinal tract, which leads to the proliferation of bifidobacteria in the human gut (Subhan, et al., 2020). **Inulin** is a viable component for developing low-calorie food products that can help regulate the glucose level of individuals with diabetes (Shoaib, et al., 2016). **Lactulose** can be administered orally or as a rectal suppository to manage hepatic encephalopathy (Tungland, 2018). **β-glucans** have been found to offer various health benefits such as regulating diabetes, averting Alzheimer's disease, obesity, hypertension, type 1 diabetes mellitus, pancreatitis, colon cancer, autism, fibromyalgia, allergy, and immunomodulatory function, as reported by (Jayachandran, Chen, Chung, & Xu, 2018). **Pectin** has been identified as a promising agent in the prevention of cancer and exhibits properties similar to those of a natural prophylactic agent against the deleterious impact of toxic cations (Emran, et al., 2022). Pectin exhibits significant efficacy in binding and eliminating mercury and lead from the gastrointestinal tract. Pectin extracted from fruits has good film-forming properties (Zhang, Chen, Dai, Cui, & Lin, 2024). **Polyunsaturated fatty acids (PUFA)** including stearidonic acid (SDA), docosahexaenoic acid (DHA), eicosapentaenoic acid (EPA), α-linolenic acid (ALA), and docosapentaenoic acid (DPA) (Pyle, 2022). The status of PUFA has been linked to various health conditions such as metabolic disorders, insulin sensitivity, neuronal development, cardiovascular and immune functions, obesity, and neuropsychiatric disorders such as suicidal tendencies and depression (Kumar, Butt, & Levenson, 2016). **Lactobionic acid (LBA)** is notable that this compound is unaffected by digestive enzymes and the gastrointestinal environment and can be metabolized by microorganisms in the gut. While the FDA has solely sanctioned the utilization of LBA as calcium salt, specifically calcium lactobionate, other food regulatory bodies are currently evaluating its approval and are anticipated to grant it in the near future (Sáez-Orviz, et al., 2022).

The effect of prebiotic incorporation on the properties of different films have been reported in this paragraph. The addition of XOS or GOS did not affect the thickness of the films (Fernandes, Guimarães, Silva, et al., 2020). The XOS can increase the tensile strength of the chitosan-based films, and approximately 92.6% XOS in films can be released in simulated gastric fluid within 60 min (Xu, Xia, Yuan, & Sun, 2019). The FOS exerted a plasticizing effect on the starch films and decreased their glass transition temperature (Bersaneti, Mantovan, Magri, Mali, & Celligoi, 2016). However, the addition of prebiotic increases the hydrophobicity, and lower the melting temperature of the films (Fernandes, Guimarães, Silva, et al., 2020).

Phenolic compounds

Phenolic compounds can characterized by an aromatic ring that is directly linked to the rings of benzene and contains a minimum of one hydroxyl group (Saranraj, Behera, & Ray, 2019). Polyphenols are commonly classified into bioactive constituents, including flavonoids, lignans, tannins, phenolic acids, stilbenes, and coumarins, based on their source, structural variability, and physiological effects. Polyphenols are recognized for their potent naturally occurring antioxidant properties and have been found to play a crucial role in a diverse array of biological and pharmacological activities, among which are but are not limited to anticancer, antiviral, hepatoprotective, antimicrobial, antiallergic, anti-inflammatory, antithrombotic, and signaling functions. Moreover, polyphenols have been identified as a potential food additive (Kumar & Goel, 2019).

Phenolic acids are common in various food groups, with legumes, oilseeds, fruits, vegetables, cereals, herbs, beverages, and spices being particularly rich sources of these compounds. **Flavonoids** have the antioxidant activity which can potentially mitigate oxidative stress by enhancing metal-chelating activity, uric acid levels, and low-molecular-weight antioxidant efficacy (Williamson, Kay, & Crozier, 2018). The scavenging of reactive oxygen species (ROS), stimulation of antioxidant enzymes, suppression of oxidases such as cyclooxygenase (COX), phosphoinositide 3-kinase (PI3K), lipoxygenase, and xanthine oxidase (XO), as well as the reduction of α-tocopheryl radicals, are among the mechanisms by which flavonoid antioxidant activity may mitigate damage arising from free radicals (Shen, et al., 2022). **Tannins** showed a correlation between the reduction in net metabolizable energy, protein digestibility, feed intake, growth rate, and feed efficiency and a certain factor (Das, Islam, Faruk, Ashaduzzaman, & Dungani, 2020). **Lignans** are typically associated with dietary fiber. Rodríguez et al., (2019) described lignans as associated with various positive impacts on well-being, such as a reduced likelihood of alleviating menopausal symptoms, prevention of osteoporosis, and decreased risk of breast cancer and heart disease. **Stilbenes** are distinguished by a fundamental 1,2-diphenylethylene framework featuring diverse substituents (T. Shen, Xie, Wang, & Lou, 2013). Notable examples include grapes (vitaceae), blueberries (ericaceae), peanuts (fabaceae), sorghum (poaceae), and pine (pinaceae). The medicinal value of these fruits has been studied in various fields, involving their anti-inflammatory, cardioprotective, antioxidative, anti-obesity, antimicrobial, and anticancer properties, as studied by (Navarro-Orcajada, et al., 2022).

The optimized incorporation of phenolic compounds in coatings and film could improve the oxidative stability and color properties. Phenolic compounds, such as anthocyanins, could be used in films and coatings as pH indicator (Eskandarabadi, et al., 2019). The sensory scores (freshness, color, taste, hardness) were reported higher in treated bell-pepper by edible coating with phenolic compounds during the storage period at different storage temperatures (N. Kumar, et al., 2021). However, addition of phenolic compounds could increasing oxygen diffusion into the product due to disruption of polymer network (Hosseini, Yaghoubi Hamgini, Jafari, & Bolourian, 2020).

Methods employed for the manufacturing of coatings and films combined with bioactive compounds

Edible films and coatings are fabricated from protein by different methods such as solvent casting, extrusion, coating, encapsulation, and so on. The bioactive compounds incorporated in the film matrix required optimal conditions during processing, storage, and after delivery. The different methods of bioactive compound incorporation and fabrication of films and coatings have been discussed in this section.

Solvent casting

The most common encapsulation of bioactive compounds and fabrication of protein film is the casting method due to the ease of laboratory scale. Globular protein has good solubility in water as well as aqueous solutions of salts and acid bases but fibrous protein is considered as water insoluble. The film-forming solution could be prepared easily by dissolving the protein in the desired solvent or adjust the pH to increase the solubility if necessary, in casting method (Fig. 1). It is convenient to add filler, and crosslinkers to enhance the physical and mechanical characteristics of the protein film (Marangoni Júnior, Vieira, & Anjos, 2020; Priyadarshi & Rhim, 2020; Umaraw, et al., 2020). The process parameters and steps could be modified in case of enzymatic or photosensitizer-induced crosslinking for improvement of the physicochemical and structural properties of the protein film (Ahammed, et al., 2021). The incorporation process of prebiotics such as solubilization, processing temperature and pH, dispersion method, casting volume, the thickness of the film after drying, could meet and obtain the desired functionality (Paulo, Baú, Ida, & Shirai, 2021).

Extrusion

Extrusion or heat press method is also used for fabricating film from egg white protin (Pranata, et al., 2019), pea protein (Huntrakul, et al., 2020), lentil protein (Ochoa-Yepes, Di Giogio, Goyanes, Mauri, & Famá, 2019), soy protein (Kumar, Sandeep, Alavi, Truong, & Gorga, 2010), zein (Wang & Padua, 2002), gelatin (Nur Hanani, O'Mahony, Roos, Oliveira, & Kerry, 2014). In this method, protein passed through an extruder consist of several heating zone (Fig. 2). The barrel temperature used in extrusion method between 85 °Cand 150 °C (Huntrakul, et al., 2020). The speed of the sample could be controlled by maintaining the speed of screws depending on viscosity. The typical extruder setup include a screen pack to control residence time and filter any contaminats. A pulling station is used o chill and collect the film. However,

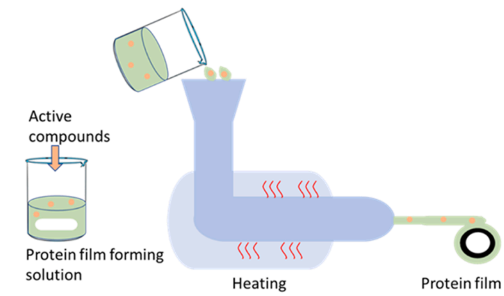

Fig. 2. Schematic diagram of the protein film fabrication by extrusion method. The film-forming solutions incorporate probiotics, prebiotics, or phenolic compounds.

the tensile strength of the film by solvent casting method has been reported 3-4 times higher the film fabricated utilizing extrusion method. Gelatin film had tensile strength between 60 to 90 MPa by casting method while 17-20 MPa by extrusion method (Park, Scott Whiteside, & Cho, 2008).

Coating

The coating does not serve as packaging; however, it can minimize the packaging's barrier specifications and limit intrinsic variables, thereby extending the food's shelf life (Md Nor & Ding, 2020). Protein from animal and plant source could be utilized for coating the food product (Matloob, et al., 2023). Edible coatings are usually applied in liquid form by dipping (Fig. 3) or spraying (Fig. 4) to form a coating on the surface of the food product (Galus & Kadzińska, 2015). The method requires expertise to produce uniform coating (Tahir, et al., 2019). Gelatin has been widely used as a film-forming component of edible coatings and used to keep fresh persimmon, tomato, cherry, bread and other fresh foods (Kingwascharapong, Arisa, Karnjanapratum, Tanaka, & Tanaka, 2020; Zhang, et al., 2021). The zein surface coating materials involved in the anti-solvent precipitation method are extensive (Yuan,

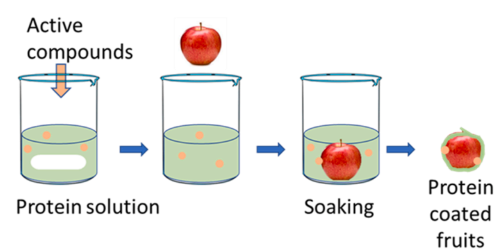

Fig. 3. Schematic diagram of the protein coating by soaking method. The coating solutions incorporate probiotics, prebiotics, or phenolic compounds.

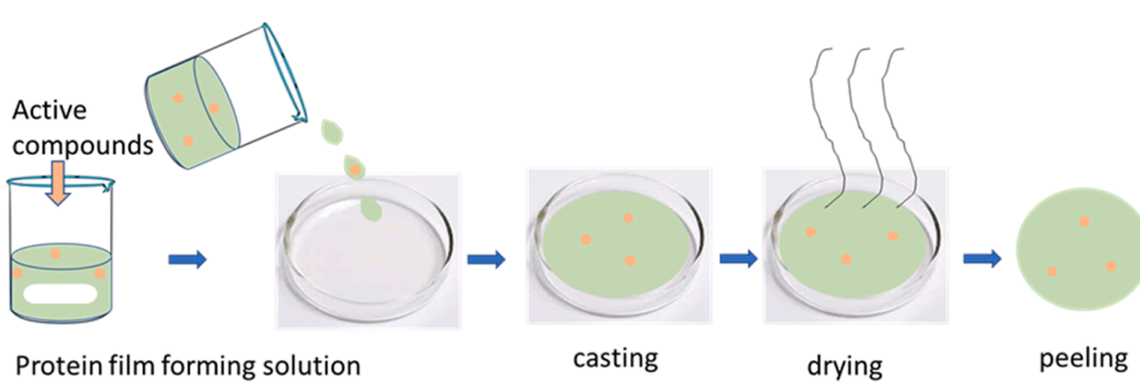

Fig. 1. Schematic diagram of the protein film fabrication by solvent casting. The film-forming solutions incorporate probiotics, prebiotics, or phenolic compounds.

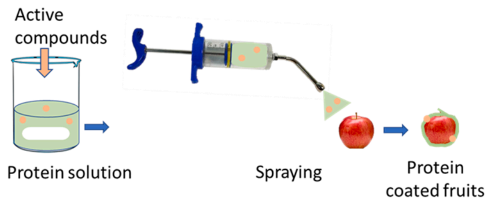

Fig. 4. Schematic diagram of the protein coating by spraying method. The coating solutions incorporate probiotics, prebiotics, or phenolic compounds.

Ma, Xu, & Wang, 2022). The dipping method involves preparing a biopolymer solution with the required conditions. After submerging the food in the coating solution for 30 seconds to half an hour, the excess solution is drained out (Kanatt, Rao, Chawla, & Sharma, 2013).

Encapsulation

Encapsulation is defined as the technique of enclosing a bioactive core within a protective layer, commonly referred to as wall materials, to safeguard a vulnerable material in the form of micro and/or nanostructures (Jayaprakash, Maudhuit, Gaiani, & Desobry, 2023). The objective is to enhance the retention of bioactive compounds for targeted, controlled, and delayed release while also defending them against environmental stresses such as moisture, oxygen, and light (Drosou, Krokida, & Biliaderis, 2017).

Freeze drying

Freeze-drying is a widely used method for dehydrating food items that are susceptible to heat damage, including bioactive vitamins, antioxidants, and natural colors. In this process, drying is carried out by dehydration of the frozen substances through sublimation so that the phenolic compound can be encapsulated efficiently (Fig. 5). Anthocyanins-rich extracted from jaboticaba pomace were encapsulated in SPI (Pereira Souza, Deyse Gurak, & Damasceno Ferreira Marczak, 2017). Microencapsulation of olive leaf extract (González-Ortega, Faieta, Di Mattia, Valbonetti, & Pittia, 2020) and *Citrus sinensis* essential oil (Citrus aurantium var. dulcis) by freeze-drying applying maltodextrin and maltodextrin or gelatin mixtures (de Araújo, et al., 2020). Freeze drying showed the phenolic compound retention efficiency of 86% which was better than the spray drying (66%) for gelatin coating production (Jovanović, et al., 2021).

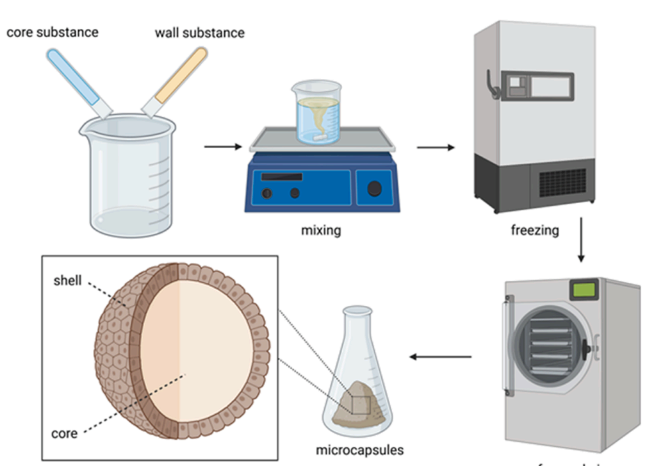

Fig. 5. Schematic illustration of freeze-drying encapsulation process using protein as the wall material (adopted from Bińkowska, Szpicer, Wojtasik-Kalinowska, and Półtorak (2024)).

Coacervation

In biopolymer pairs of protein-polysaccharide mixtures, complex coacervation can be achieved by precise control of the extrinsic factors that result in macroions with opposite charges interacting through electrostatic forces (Schmitt, et al., 2005) (Fig. 6). According to previous studies, gelatin can create coacervates and complexes when combined with various polysaccharides, including alginates (Nirmala Devi & Kakati, 2013), pectin (Silva, Favaro-Trindade, Rocha, & Thomazini, 2012), sodium carboxymethyl cellulose (Devi & Maji, 2011), carrageenan (Devi & Maji, 2010), chitosan (Kim, et al., 2006), and zein protein (Ahammed, Easdani, Liu, & Zhong, 2023). These findings are significant as they demonstrate the potential for gelatin to be used in the microencapsulation of a wide range of bioactive ingredients. Gelatin (types A and B) was combined with gum acacia as a wall material to encapsulate garlic oil (Siow & Ong, 2013) and pheromone (Kong, Gu, Zhu, & Zhang, 2009) via complex coacervation. The retention of tea polyphenol was 24.46% (Chen, Xiao, Cai, & Liu, 2020) in the gelatin–zein composite film without encapsulation, and increased to 36–39% after encapsulation by coacervation (Ahammed, et al., 2023).

Gelation

The process of encapsulation can be attained through the gelation and aggregation of protein matrices due to the amphiphilic nature of entrapping phenolic compounds (Augustin & Hemar, 2009). Gelation can be obtained by acid-, ionic-, cold-set-, and heat-set treatment. The pH value of the protein solution is modified to a level that exceeds its IP, and a bioactive compound is added. After that, to form the particular gels, the pH is adjusted to its IP to enhance the electrostatic interactions (Augustin & Hemar, 2009). Ionic gelation is a technique that is dependent on the electrostatic interactions between cations and the carboxylic groups of proteins. To encourage the gelation of proteins like casein, calcium ions are frequently utilized. At first, heating is applied to obtain the protein solution, and then cool it and the bioactive compound for encapsulation in the cold-set gelation process (Tavares, Croguennec, Carvalho, & Bouhallab, 2014). The bioactive compounds are introduced into the protein matrix prior to undergoing heat treatment, as per the findings of Betz and Kulozik (2011). According to Chen, Remondetto, and Subirade (2006), the primary method involves the application of heat to unravel the peptide chains, thereby exposing the hydrophobic

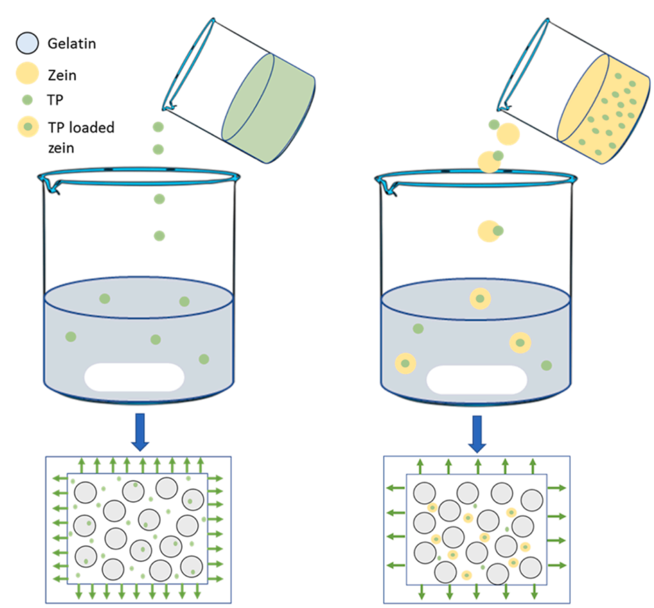

Fig. 6. Schematic representation of the protein film illustrating the encapsulation of phenolic compounds using the coacervation method for achieving controlled release of active compounds.

amino acid residues to entrap the phenolic compounds and create a protein network with a three-dimensional structure. Various gelation techniques were utilized in combination to produce whey protein nanoparticles, as reported by Sadeghi, Madadlou, and Yarmand (2014).

Spray drying

The food sector has employed spray drying encapsulation (SDE) for many years since it is a reasonably cheap technique. Different carbohydrates, gums, proteins, and modified starch have been reported to be used as a wall material for encapsulation using the spray drying method (Borrmann, Pierucci, Leite, & Leão, 2013). Animal-derived proteins, namely casein and whey protein, are extensively adopted to assist in the encapsulation of various bioactive compounds due to their exceptional coverage, emulsifying properties, and ability to form films. On the other hand, plant proteins (such as soy protein) are gaining increasing attention in the food industry due to their lower allergenicity compared to animal proteins. Spray drying was used to encapsulate phenolic compounds to produce gelatin coating (Fig. 7) but the poor retention efficiency results a loss of ~34% of polyphenol compounds (Jovanović, et al., 2021).

Electrospinning

In the process of electrospinning, electrically charged jets are created from viscoelastic polymer solutions using electrostatic forces, and when the jets are dried, they make ultrathin continuous fibers. Polymer concentration, solution viscosity, applied voltage, tip-to-collector distance, flow velocity, humidity, surface tension, conductivity, and temperature are variables that affect the electrospinning process (Drosou, et al., 2017). A large surface area per unit mass, high gas permeability, small interfibrous pore size, and high porosity are just a few of the characteristics that electrospun nanofibers coating films display. The majority of these attributes are essential when using these substances as carriers to ensure the delivery of bioactive agents (Saeed & Park, 2010). SPI, WPC, zein, gelatin, casein, and WPI are typical proteins utilized as encapsulating materials in electrospinning. β-carotene was reported to be encapsulated in ultrafine zein fibers via electrospinning, which exhibited higher light stability in contrast to the non-encapsulated control (Fernandez, Torres-Giner, & Lagaron, 2009). According to Neo et al. (2013), the antioxidant properties of gallic acid remained intact even after its incorporation into zein electrospun fibers. Phenolic compound like (−)- epigallocatechin gallate was encapsulated in electrospun zein fiber successfully, and the process of immobilizing (−)-epigallocatechin gallate was observed to take place upon aging the fibers for a minimum duration of 24 hours under arid conditions (Li, Lim, & Kakuda, 2009). The present study encapsulated fish oil, which is abundant in omega-3 fatty acids, within zein fibers. The findings revealed that electrospun zein fibers exhibited superior oxidative stability when compared to fish oil that was not encapsulated (Moomand & Lim, 2014).

Opportunities and limitations

Protein has emerged as a prominent wall material for encapsulating bioactive compounds, serving as a protective barrier around the core material. Selecting appropriate methods for the production of protein coatings and films is quite difficult. The advantages and limitations of different manufacturing mehods of film and coating have been discussed in this section.

The inexpensive processing equipment and promising properties made the casting method a potential candidate for bioactive protein-based packaging production (do Val Siqueira, Arias, Maniglia, & Tadini, 2021). However, the long drying time and high energy consumption hinder the application in industrial applications. Extrusion is a continuous and high performance process, advantageous for industrial scale (Reddy & Yang, 2013). The water barrier properties reported lower for film by extrusion method which limit the application (Karkhanis, Stark, Sabo, & Matuana, 2018). The temperature required in extrusion method is over 100 °C which limits the incorporation of probiotics.

The efficient dip coating technique doesn't require any expensive

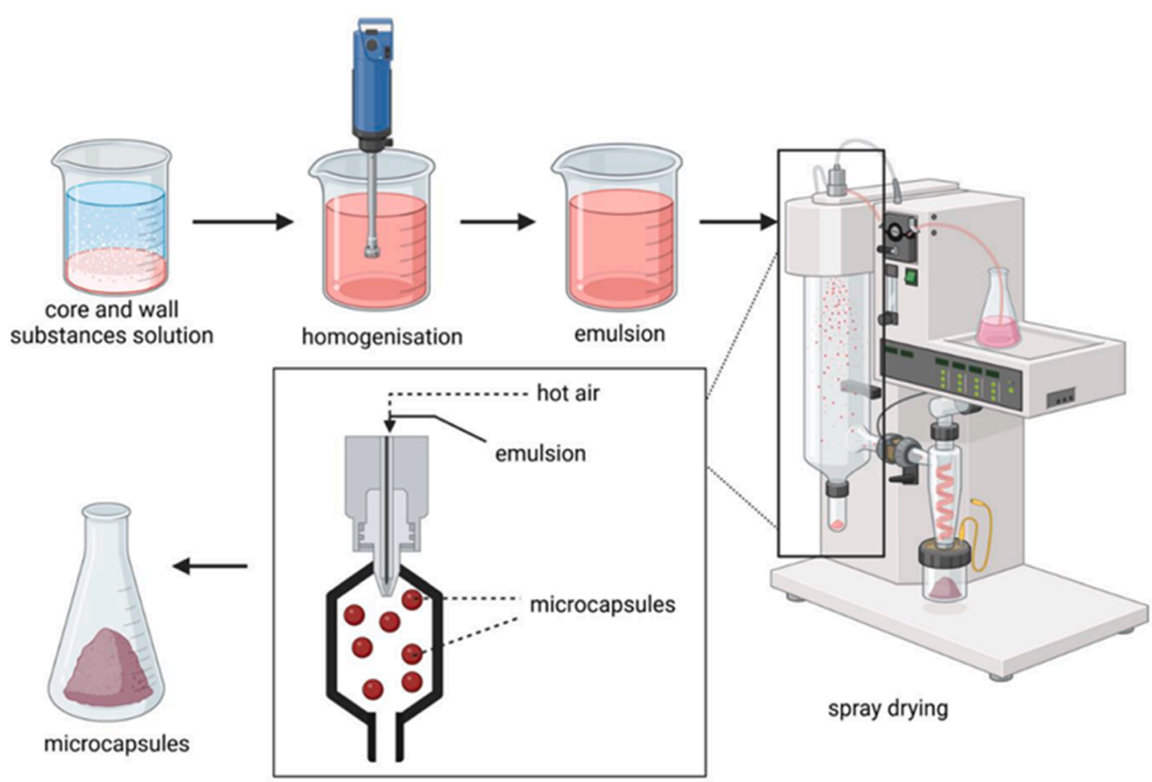

Fig. 7. Schematic representation of spray-drying encapsulation technique utilizing protein as a wall material (adopted from (Bińkowska, et al., 2024)).

equipment, saves time, and is quite successful at keeping and maintaining the food quality. The uniformity of coating thickness is a key factor which can be controlled easily, and multilayer coating can be applied by spray coating (Andrade, Skurtys, & Osorio, 2013). The coatings may have a number of serious drawbacks, including insufficient mechanical strength and inadequate water barrier qualities (Cong, et al., 2023; Dissanayake, et al., 2023). Permeability against water vapor and oxygen was reported low by freeze drying method (Erdem & Kaya, 2022).

Spray coating is particularly efficient when combined with other treatments. Additionally, the use of spraying systems can help avoid coating solution contamination, control the solution temperature, and improve continuous production automation. The prebiotics are incorporated in the coating materials and manually spread over food evenly using sterile utensils. The coating is dried under specific conditions before packaging and storage (Priyadarshi & Rhim, 2020). However, these methods are still limited to encapsulated bioactive compound applications. Further research could develop a method for the application of these encapsulated bioactive compounds for film fabrication. Despite recent advancements, protein films may exhibit sensitivity to moisture, leading to potential issues with moisture absorption or loss, affecting their mechanical properties and shelf-life stability (Ahammed, et al., 2021). Protein films and coatings might be sensitive to allergens and have higher production costs compared to other edible films and coatings.

Health benefits

Consumers exhibit a preference for food products that are fortified with naturally occurring components that confer health benefits while preserving their nutritional and sensory attributes, as well as those that are fresh, minimally processed and free of chemically manufactured components (Galanakis, 2021).

The utilization of coatings and films containing prebiotics presents a promising technological approach for enhancing the viability and preserving the characteristics of probiotic bacteria in food products (Espitia, Batista, Azeredo, & Otoni, 2016). Encapsulation using SPI as a coating materials significantly ($p < .05$) improved the survival of probiotics under simulated gastrointestinal and thermal conditions (Zeashan, et al., 2020). However, the probiotic bacteria need nutrient for survival, therefore, addition of prebiotic increase the survival rate of bacteria in the film. The addition of probiotics into edible coatings and films, done alone or in combination with prebiotics, was found to promote the stability and effectiveness of probiotic bacteria through a synbiotic effect (Mohanty, Misra, Mohapatra, & Sahu, 2018). The presence of lactobionic acid improved the viability of *Lactobacillus plantarum* in the gelatin film (Sáez-Orviz, et al., 2022). Lactic acid bacteria have the ability to play a protective role at the gastrointestinal level by inhibiting the biological activity of genotoxic compounds, and thus preventing DNA damage, an early event in the carcinogenesis (Garcia-Gonzalez, et al., 2020). Bacteria can reduce the genotoxicity of such chemical molecules by either binding or bio-converting them to unreactive compounds (Walia, Keshani, Sood, & Kanwar, 2014).

Prebiotics have traditionally been incorporated into various food formulations, including meat, dairy, baked goods, and beverages, to enhance their technological and sensory properties, thereby enhancing their ability to act as a sugar substitute, mouthfeel, and texture. According to recent studies, the disintegration of prebiotics hinders the targeted activation of bacteria that enhances overall health (de Paulo Farias, de Araújo, Neri-Numa, & Pastore, 2019; Neri-Numa & Pastore, 2020). The fermentation of inulin has been shown to increase urinary hippurate concentrations decreased obese and diabetics in clinical studies (Carlson, Erickson, Lloyd, & Slavin, 2018).

Singh et al., (2020) have documented the various advantages of phenolic compounds, for example, their antimutagenicity, antioxidation, neuroprotection, anti-inflammatory, antitumor, anti-atherosclerosis, antiallergic, and cardioprotection properties. Consequently, various phenolic compounds are being integrated into comestible films and coatings. Vilela, et al., (2017) reported the utilization of ellagic acid, phenolic acid, and chitosan in the production of functional food-packaging films that exhibit prominent antimicrobial, antioxidant, and UV-light-resistance properties. The incorporation of gallic acid in several edible coatings has been observed to effectively delay lipid oxidation, as reported in studies conducted by (Cao, Warner, & Fang (2019)) and (Xiong, Kamboj, Ajlouni, & Fang (2021). The inclusion of caffeic acid and p-coumaric acid in processed fish and related goods has been shown to delay oxidative degradation, as reported by (Panda, Yang, Chang, & Su, 2019). The carboxymethyl cellulose film's antioxidant and antibacterial properties were enhanced by resveratrol and eugenol (Aminzare, Moniri, Hassanzad Azar, & Mehrasbi, 2022).

Conclusion

This review highlighted the advantages of protein based edible films and coating, different methods of fabrication and encapsulation of bioactive compounds to obtain their desired nutritional values. Probiotics, prebiotics, and phenolic compounds need to be promising processing approaches for the protection during storage, and control release in the gastrointestinal tract to obtain the health benefits. Incorporating bioactive compounds in protein films or coatings may be more efficient than adding them directly to the foodstuff. Edible protein films and coatings have been developed to contain bioactive compounds that are effective in controlling the release and obtaining the highest health benefits. The present trends involve the development of edible films and coatings that possess distinctive characteristics such as the ability to incorporate functional compounds such as probiotics, prebiotics, antioxidants, natural colors, flavors, aromatics, and vitamins and assess the interactions, control the release, and ensure the functionality after releasing which could be achieved by incorporating bioactive compound in the protein based edible films and coatings. The casting method for film preparation and coacervation for encapsulation is the most promising technique for protein-based films and coatings for delivering bioactive compounds. However, the factors influencing the activity of bioactive compounds should be considered as the process parameters for the successful utilization of edible films and coatings for delivering probiotics and prebiotics.

Ethical statement

This study does not contain any human or animal study.

CRediT authorship contribution statement

Myat Noe Khin: Writing – original draft, Data curation, Investigation, Funding acquisition. **Shabbir Ahammed:** Writing – original draft, Validation, Investigation, Conceptualization, Software. **Md. Murtuza Kamal:** Visualization, Supervision, Investigation, Writing – review & editing. **Md Nazmus Saqib:** Visualization, Software, Investigation, Writing – review & editing. **Fei Liu:** Visualization, Investigation. **Fang Zhong:** Writing – review & editing, Visualization, Supervision, Resources, Conceptualization.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

No data was used for the research described in the article.

Acknowledgment

This research was supported by the National Natural Science Foundation of China (31871846, 31801589, 32350410429). The research was also supported by "The Jiangsu Funding Program for Excellent Postdoctoral Talent (2023ZB887)" and the program of "Collaborative Innovation Center of Food Safety and Quality Control in Jiangsu Province", China.

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