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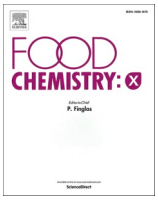

Recent progress in plant-based proteins: From extraction and modification methods to applications in the food industry

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ABSTRACT

Plant proteins can meet consumers' demand for healthy and sustainable alternatives to animal proteins. It has been reported to possess numerous health benefits and is widely used in the food industry. However, conventional extraction methods are time-consuming, energy-intensive, as well as environmentally unfriendly. Plant proteins are also limited in application due to off-flavors, allergies, and anti-nutritional factors. Therefore, this paper discusses the challenges and limitations of conventional extraction processes. The current advances in green extraction technologies are also summarized. In addition, methods to improve the nutritional value, bioactivity, functional and organoleptic properties of plant proteins, and strategies to reduce their allergenicity are mentioned. Finally, examples of applications of plant proteins in the food industry are presented. This review aims to stimulate thinking and generate new ideas for future research. It will also provide new ideas and broad perspectives for the application of plant proteins in the food industry.

1. Introduction

Proteins are essential nutrients in the human diet. Animal proteins present concerns related to health, safety, environmental contamination, and resource availability (Zhang, Jing, et al., 2023). Driven by consumers' demand for environmentally friendly, nutritious, sustainable, and humane choices, the plant proteins industry has grown rapidly over the past decades (Hertzler, Lieblein-Boff, Weiler, & Allgeier, 2020). Plant proteins are gradually replacing animal proteins as an emerging option. Common sources of plant proteins mainly include pulses (pea, fava bean, lentil, lupin, and chickpea), cereals (wheat, corn, rice, barley, sorghum, rye, oat, and millets), pseudocereals (quinoa, amaranth, buckwheat, and chia seeds), seeds (chia, linseed, sesame, pumpkin, and sunflower), nuts (almonds, cashew, and peanut), and others (Thakur, Pandey, Verma, Shrivastava, & Singh, 2023).

Plant proteins are abundant in raw materials and need to be extracted to obtain them. Extraction methods fall into two categories: conventional extraction methods and novel extraction techniques. Conventional methods are restricted by long extraction time, low extraction selectivity, expensive high-purity solvents, large amounts of solvent evaporation, and degradation of thermolabile proteins (Selvamuthukumaran & Shi, 2017). To improve extraction recovery and reduce protein degradation during extraction, researchers are now focusing more on novel technologies. These techniques have less negative impact on the environment, as they use a minimum of harmful chemicals and solvents (Pojic et al., 2018).

Multiple investigations have demonstrated the biological properties of plant proteins for overall health and wellness, including their antidiabetic, anti-cancer, anti-oxidant, and nephroprotective effect, as well as their capacity to reduce cardio-metabolic risk factors, regulate appetite and lipid metabolism, and modify the gut microbiome (Bouchard et al., 2022). However, the utilization of plant proteins in the food industry remains a challenge due to their poor techno-functional properties, such as water retention, solubility, and emulsifying as well as gelling properties, which are significantly lower than those of animal proteins (Sim, Akila, Chiang, & Henry, 2021). To overcome these disadvantages, various modification methods have been applied to modify the internal structure of plant proteins and improve their bioactive and techno-functional characteristics, thus broadening their applications as nutritional ingredients (Nasrabadi et al., 2021). Physical modification

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means altering the structure of proteins using a force field to improve their biological potential, techno-functional properties, and digestibility. For example, Baskinci and Gul (2023) investigated the effect of high-pressure homogenization on the microstructure, technological function, and rheological properties of sesame protein isolates. In addition, chemical modification is applied to construct proteins with enhanced and/or altered properties through chemical solvents or chemical reactions. For example, Nosouhian, Hojjatoleslamy, Goli, Jafari, and Kiani (2023) utilized the Maillard reaction to enhance the emulsifying capabilities of the soy protein isolate for food application. As for biological modification, biological means such as enzymes, fermentation, and germination are applied to degrade or construct protein structures to enhance the bioactive properties of proteins. For instance, Cen et al. (2024) found that fermentation could improve the nutritional value, active substances, amino acids, metabolites, and antioxidant activity of the treated raw proteins.

We searched for studies on plant proteins in the last 5 years using the Web of Science database, and the visualization figure is plotted in Fig. 1 (Data accessed on 5th March 2024). It shows that most of the research on plant proteins focused on arabidopsis, expression, protein, and growth. However, there are deficiencies regarding the extraction, modification, and application. Therefore, to fill the gap of knowledge in these areas, we first summarize the challenges and limitations of traditional extraction methods for plant proteins and update the research progress on novel extraction processes. In addition, we also provide up-to-date details of the principal techniques used to modify the functional properties and optimize the quality of plant proteins. Finally, based on research hotspots, four plant-based protein products are discussed, including food packaging films, bioactive peptides, food emulsion gels, and encapsulating materials of bioactive compounds. This review will provide readers with a clear understanding of plant proteins and help to further expand the potential uses of plant proteins.

2. Extraction methods of plant proteins

In nature, plant proteins exist as heterogeneous mixtures combined with Phyto components including carbohydrates, oligosaccharides, lipids, and secondary metabolites. Therefore, extraction is usually carried out to obtain proteins that differ in profile, quality, and functionality. Extraction methods can be categorized into two types: conventional methods (alkaline extraction, acid extraction, salt extraction, and dry fractionation) and novel methods (ultrasound-assisted extraction, pulsed electric field, deep eutectic solvent, and enzyme-assisted extraction). In this section, conventional and novel extraction methods are presented to enhance the basic knowledge of extraction technologies.

2.1. Conventional protein extraction methods and their limitations

Conventional methods, such as wet extraction methods (alkaline extraction, acid extraction, and salt extraction) and dry fractionation, were usually employed to extract plant proteins. The schematic diagram of conventional extraction methods is shown in Fig. 2.

Wet extraction refers to extracting proteins in aqueous solvents or chemicals such as alkali, acids, or salt, and then precipitating or recovering the proteins. Alkaline extraction is by far the most common conventional protein extraction method as it is simple, economical, and efficient. As for alkaline extraction, proteins become negatively charged and solubility increases when the pH is raised above the isoelectric point. The insoluble components, which mostly consist of non-protein ingredients, are then removed by centrifugation (Gençdag et al., 2021). The steps for acid extraction are similar to those for alkaline extraction. Acidic solutions (e.g. butanol, pentanol, hexane, and acetone) are commonly used for acidic extraction. With the addition of acid, the pH of the protein solution is gradually lowered below the

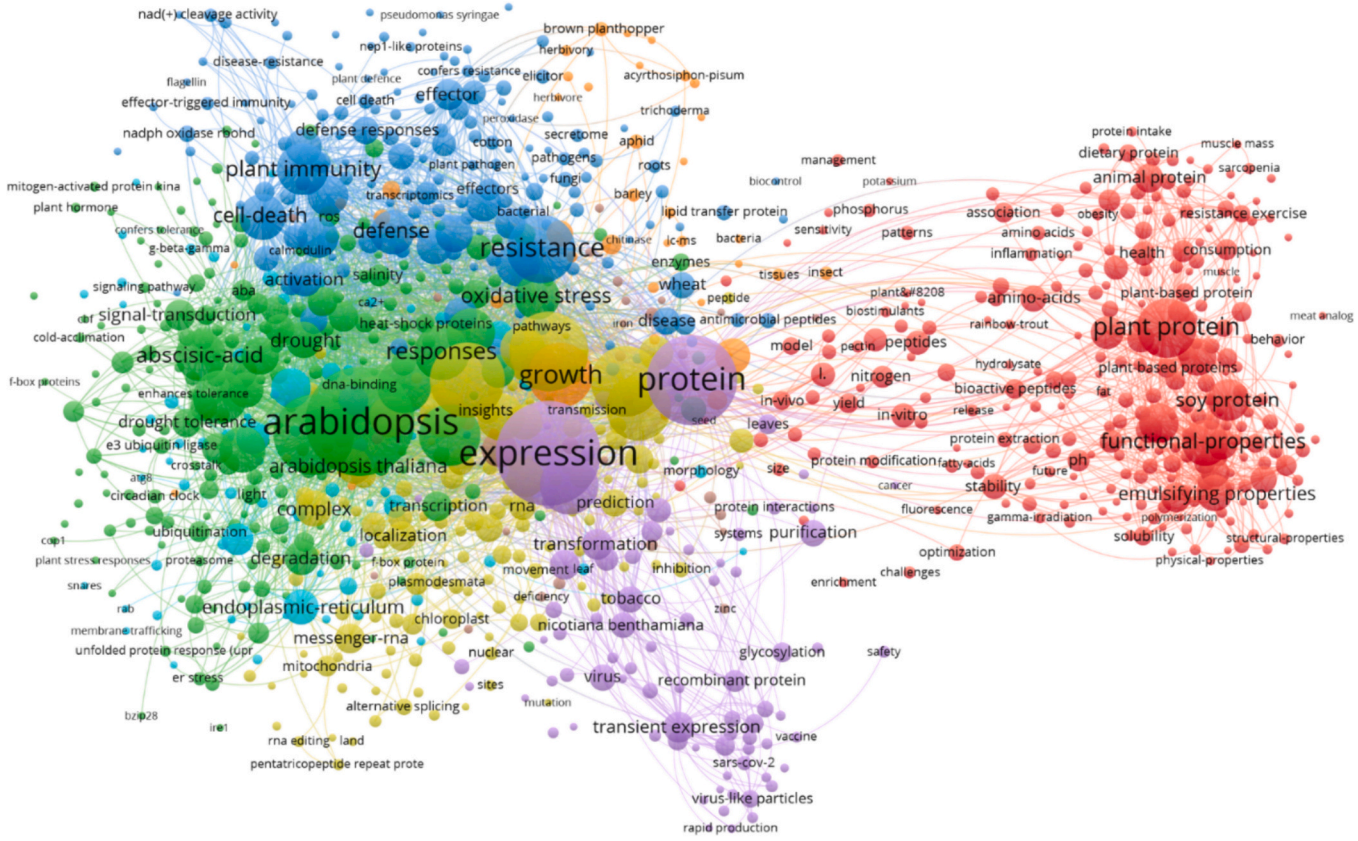

Fig. 1. Overlay visualization of research points of plant proteins in recent five years.

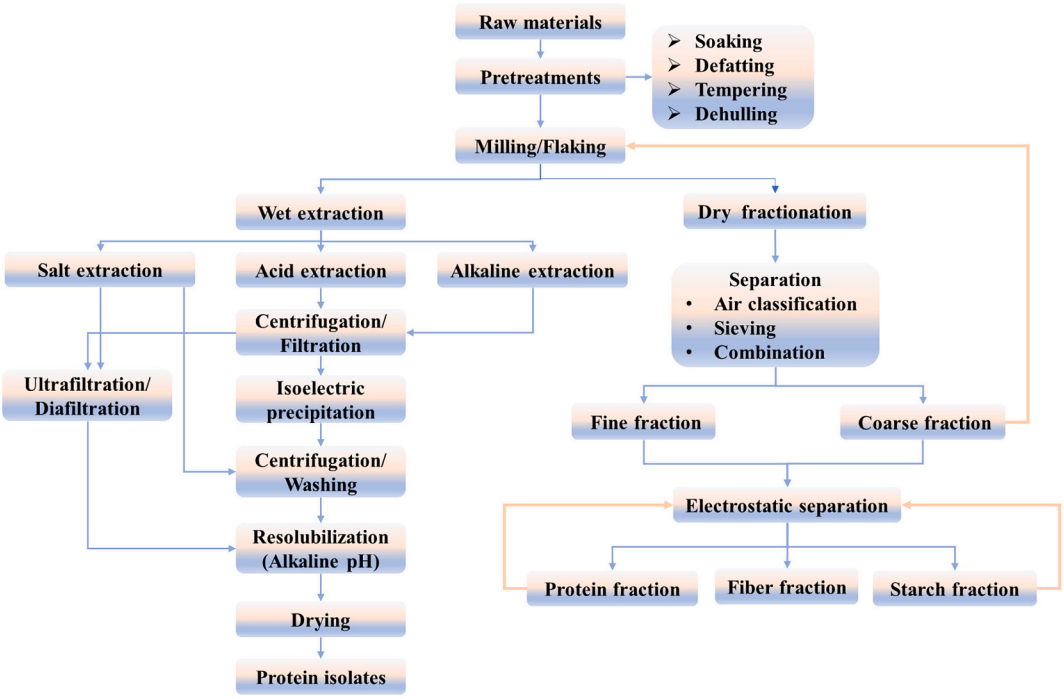

Fig. 2. The schematic diagram of wet extraction and the dry fractionation process.

isoelectric point, a positive charge is generated, and protein solubility increases. Immediately after, the pH is adjusted to the protein isoelectric point and soluble proteins are aggregated and subsequently enriched using precipitation, centrifugation, or filtration (Momen et al., 2021). Neutral pH salt solutions such as sodium, calcium, or potassium chloride are commonly used reagents for salt extraction. The principle of salt extraction is based on the precipitation of proteins by the phenomena of salinization and salting-out of proteins, followed by the removal of insoluble matter by sedimentation, decantation, sieving, and centrifugation. Then, the supernatant is desalted and dried to obtain the protein. Salt-extracted proteins are preferred for applications such as foaming, emulsifying, and gelling because they are more soluble and contain less denatured and aggregated proteins (Shrestha, Hag, Haritos, & Dhital, 2023).

As Fig. 2 shows, the dry fractionation process is based on the principle of mechanically separating proteins from starch and other cellular components. Firstly, the plant materials have been pre-treated, such as dehulling, immediately followed by grinding. Then, particle size reduction techniques, including milling, are used to fragment the plant starch matrix as well as fiber-rich cell wall material to produce separate starch granules and proteasome fragments (Schutyser, Pelgrom, van der Goot, & Boom, 2015). Subsequently, starch ($\geq$ 20 μm), fiber, and protein (1–3 μm) fragments of widely varying sizes are separated using air classification, sieving, or their combination based on size and density, followed by electrostatic separation (Pulivarthi et al., 2023).

However, traditional wet extraction methods are limited by the presence of harmful solvent residues, environmental pollution, and energy consumption. Furthermore, conventional methods may result in low protein extraction rates and poor extraction quality. For example, alkaline extraction reduces the digestibility of proteins, damages the structure of amino acids, and introduces a bitter flavor (Perovic and Antov, 2022). The use of acid extraction is not satisfactory as it affects the solubility and gel properties of the extracted proteins. Dry fractionation processes, such as air separation, produce residual proteins in the starch fractions which limits the protein yield of air separation. Solvents are typically used in large quantities in many traditional extraction processes and are characterized as highly volatile, flammable, and toxic. It is also worth noting that these harmful solvents can remain on proteins and can influence human health through absorption into the body. As a result, research into innovative extraction methods is underway at home and abroad to address the shortcomings and deficiencies of traditional methods.

2.2. *Research progress of novel extraction methods*

Compared to conventional protein extraction methods, the novel techniques have obvious advantages as they are inexpensive, environmentally friendly, highly efficient, and produce versatile end products. The following content describes recent advances in four innovative extraction methods and their schematic diagram is shown in Fig. 3.

2.2.1. *Ultrasound-assisted extraction (UAE)*

Ultrasonic technology relies on the generated mechanical waves with frequencies ($>$ 20 kHz) above the range of human hearing (20 Hz to 20 kHz). High-power ultrasound frequencies, between 20 and 100 kHz, are commonly used in food processing. The basic principle of UAE is explained by the phenomenon of cavitation, in which bubbles form in a solution, increase in volume, and finally explode (Bernardi et al., 2021) (Fig. 3A). Cavitation releases large amounts of mechanical and thermal energy, which benefits the extraction of biomolecules from solid matrices. It also causes the plant cell matrix to rupture, creating channels through which surrounding solvents (alkalis or acids) can enter the cell through the pores and dissolve proteins (Eze, Kwofie, Adewale, Lam, & Ngadi, 2022).

Compared to conventional methods, ultrasound is a promising eco-innovation for the food industry due to its lower time and energy requirements, cheaper installation and maintenance costs, and reduced processing temperatures (Flores-Jiménez, Ulloa, Ortiz-Basurto, & Urías-Silvas, 2023). Numerous studies focused on optimizing the conditions (such as pH, temperature, and time) of UAE to obtain the maximum protein yield. For instance, Orellana-Palacios et al. (2022) found that the highest extraction rate (17.3%) and protein content (65.6%) were achieved at a pH of 10.5, a temperature of 41.8 °C, and a time of 26.1 min. Another study obtained an 82.6% pea protein recovery when the extraction factors were set at a solid: liquid ratio of 1:11.5 (g: mL), pH 9.6, 13.5 min extraction time, and 33.7% ultrasonic amplitude (Wang,

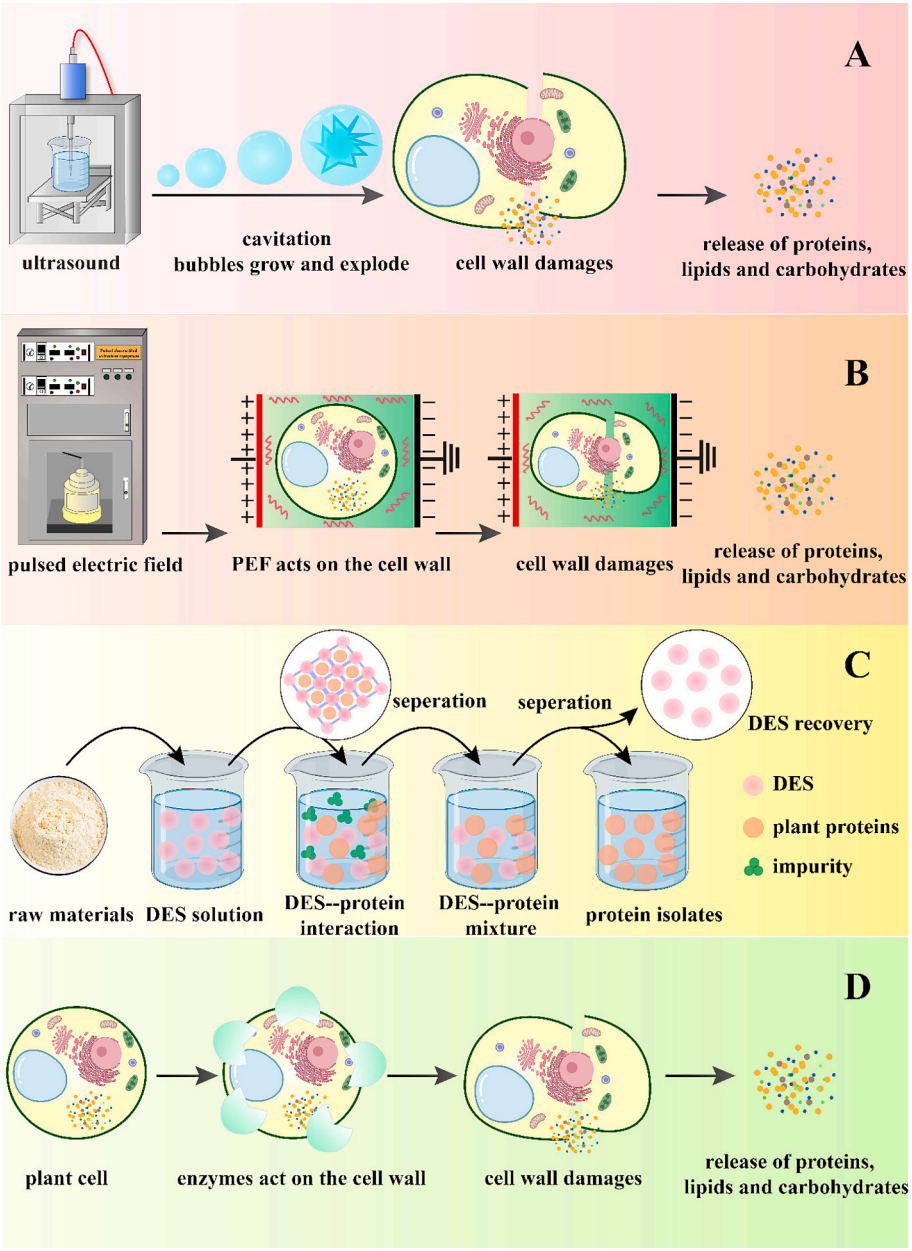

Fig. 3. Schematic diagram of four innovative extraction methods. (A) Ultrasound-assisted extraction (UAE); (B) Pulsed electric field (PEF); (C) Deep eutectic solvent (DES); (D) Enzyme-assisted extraction (EAE).

Zhang, Xu, & Ma, 2020). Purdi et al. (2023) observed that ultrasonic conditions set to work at 80% amplitude for 30 min with a duty cycle of 60% resulted in a significant increase in protein yield (76.83%) as compared to the conventional extraction method (32.48%). Li et al. (2021) used UAE to extract defatted mulberry seed proteins under the optimal conditions of a solid-liquid ratio of 1:40, a temperature of 60 °C, an extraction time of 9 min, and an output power of 600 W.

Although UAE is a promising extraction technique, some limitations must be considered. Firstly, the optimal conditions for UAE vary due to the diversity of plant protein sources. Proteins tend to decompose or denaturant at unsuitable UAE temperatures. Furthermore, UAE-induced free radicals oxidize proteins, affecting the structure and function of extracted proteins. It is also worth noting that the industrial scale of UAE has not yet been achieved. Therefore, it is important to optimize extracting conditions, control the temperature during sonication, and expand pilot-scale research and industrial production of UAE.

2.2.2. *Pulsed electric field (PEF)*

PEF is the application of electrical pulses of very short time (10^{-4} to 10^{-2} s) and quite high amplitude (0.1–80 kV/cm) as a non-thermal process. The principle behind the use of PEF to improve extraction is that when plant cells are exposed to a given electric field, mechanical damage to cells results in the formation of temporary or permanent porous structures in tissues, a phenomenon known as electroporation (Arshad et al., 2021). This increases the permeability of the cell membrane to ions and macromolecules, thereby facilitating the release of intracellular contents such as proteins, lipids, and carbohydrates (Fig. 3B).

The application of PEF-assisted protein extraction has become a new trend, offering many advantages over traditional methods, such as improving food quality, decreasing water consumption, reducing emissions, increasing energy efficiency, and recovering by-products from food waste (Zhang, Zang, et al., 2023). According to Käferböck et al. (2020), an increase of approximately 90% in C-physio-cyanin extraction

was achieved by PEF cell disruption compared to bead milling. Similarly, treatment with PEF at 2.3 kV for 25 min resulted in a 20.71–22.8% increase in rice bran protein extraction efficiency compared to conventional alkaline extraction (Thongkong et al., 2023). In another study, the protein concentration extracted from PEF-pretreated samples increased by 28.1% compared to untreated samples at an energy input of 6.41 kJ/kg (Andreou, Psarianos, Dimopoulos, Tsimogiannis, & Taoukis, 2020). In general, temperature, pH, duration, operating time, electric field strength, conductivity, pulse frequency, and processing energy can affect the extraction effect of PEF. As a relatively new method, PEF has few applications in plant protein extraction, so further research is required to establish suitable extraction parameters and to find the optimal combination approach with other extraction methods.

2.2.3. Deep eutectic solvent (DES)

DES refers to eutectic mixtures formed from Lewis or Brønsted acids or bases, which is composed of a hydrogen bond acceptor (HBA) and a hydrogen bond donor (HBD) (Hou et al., 2022). Typical HBA includes quaternary salts, some amino acids, and metal ions, while typical HBD is comprised of alcohols, carboxylic acids, amides, amino acids, and carbohydrates.

DES has attracted attention because it is recyclable, non-toxic, non-flammable, thermally and chemically stable, easy to prepare, highly pure, highly biodegradable, and low cost. As an emerging extraction technology, DES can be used as an extraction medium for bioactive substances such as lipids, carotenoids, polysaccharides, levodopa, polyphenols, etc. (Silva, Demuner, et al., 2023). Several studies have also been conducted on the use of DES for the extraction of proteins from different plant sources, for example, pumpkin seed, oat, soybean, spirulina, and processing by-products (such as sea buckthorn seeds, bamboo shoots wastes), promoting the further application of DES in food chemistry (Lin, Jiao, et al., 2021). DES extraction mainly includes solid-liquid extraction and liquid-liquid extraction, of which liquid-liquid extraction is divided into aqueous two-phase extraction and liquid-liquid micro-extraction (Patra et al., 2023). As Fig. 3C shows, taking solid-liquid extraction as an example, the basic procedure of DES extraction is to mix pre-treated raw materials with DES, and the proteins in the raw materials interact with DES to form aggregates. Subsequently, the impurities can be removed by centrifugation and to obtain the protein-DES mixtures. Following that, the protein isolates are separated from the DES-protein system by back-extraction while DES can be recovered (Zhou et al., 2022).

Factors affecting the DES extraction process include mass of DES, salt, raw materials, temperature, time, pH, and instrumental parameters. Exploring the appropriate conditions is essential for protein extraction. Chen, Chaihu, et al. (2021) extracted soy protein using DES and obtained the optimal extraction conditions: extraction temperature of 60 °C, liquid-solid ratio of 10:3, stirring speed of 873 rpm, and time of 3.9 h. Yue et al. (2021) found that oat proteins were better extracted with a choline chloride-butanediol molar ratio of 1:3 (independent of water presence) when extracted at 80 °C for 90 min.

Despite the great potential and advantages of DES extraction, it has not yet been fully developed and applied to the extraction of plant proteins. In addition, the environmental compatibility and biodegradability of DES, particularly the biological effects of DES, still need to be investigated. Finally, how to achieve effective recycling of DES remains to be solved. Therefore, further research is necessary to address the limitations of DES and to determine whether DES-extracted proteins can be applied in the food industry.

2.2.4. Enzyme-assisted extraction (EAE)

The plant cell wall mainly consists of a variety of interconnected polysaccharides such as starch, cellulose, hemicellulose, and pectin, which form a barrier to block the release of proteins from the cell during the extraction process. As Fig. 3D shows, enzymes hydrolyze the plant cell wall and destroy the cell matrix as a catalyst for the biological reaction, facilitating the release of the extracted material into the solvent, accelerating the extraction rate, and increasing the yield (Lu, Li, Wang, Wang, & Qin, 2023). Pectinases, cellulases, hemicellulases, amylases, and proteases are commonly used for EAE (Lubek-Nguyen et al., 2022). One enzyme or a mixture of several enzymes can be employed.

EAE has been proven to improve extraction efficiency, shorten extraction time, reduce bioagent damage, and be suitable for heat-sensitive and unstable ingredients. Coniglio, Díaz, Barua, Albertó, and Zapata (2022) compared EAE with commercial EAE and conventional extraction, finding that EAE released 557–827% more protein content than those at 0 h. Compared to nanoparticles prepared from alkali-extracted proteins, those from enzymatically extracted proteins have stronger structural and functional properties (Perovic & Antov, 2022). A study comparing EAE with alkaline and salt extraction found that EAE had the highest protein content, the best solubility, and other improved physicochemical properties (Koysuren et al., 2021).

The main conditions that affect the efficiency of EAE of proteins include temperature, pH, enzyme loading, mode of enzyme action, extraction time, substrate availability, and solvent system. Response surface methodology and orthogonal test design were used to optimize the effective parameters of EAE. A previous study showed that the optimum conditions for oilseed rape leave protein extraction were: temperature (42.8 °C), amylase concentration (18,446 U), and time (4.44 h), resulting in an extraction rate of 9.56% and a protein content of 89.41% (Kaur & Bhatia, 2022). A high extraction rate of green coffee proteins (70%) and an 80% reduction in enzyme consumption were achieved by applying extraction conditions (solid-liquid ratio of 1:17.5 and 0.1% alkaline protease content). EAE exhibits great potential to be applied in extracting plant proteins with increased techno-functional properties. However, its commercial applications are limited by the cost and activity of some enzymes.

2.2.5. Combination of different extraction methods

Although the above novel extraction methods have their strengths over conventional extraction methods, they also present some constraints such as high cost and low equipment utilization, therefore multiple studies have combined the above extraction methods to overcome these drawbacks. Hildebrand et al. (2020) combined UAE with a single solvent, sequential solvent, and enzyme to maximize the recovery of proteins. Another study demonstrated that the recovery of mulberry leaf protein increased by 171.76% when multi-frequency ultrasound-assisted cellulase extraction was applied instead of traditional extraction methods (Zhao, Liu, et al., 2023). Sun et al. (2022) extracted oleosin protein using an ultrasound-assisted salt method, which resulted in a 17.6% higher yield and 122.9% higher solubility of oleosin protein compared to the conventional method. Compared to standard alkaline extraction methods, Görgüç et al. (2020) found that vacuum-ultrasound-assisted extraction and vacuum-ultrasound-assisted enzymatic extraction increased protein yields by 31.0% and 41.6%, respectively. PEF can also be used in combination with other techniques for optimal extraction. It has been reported that the combined methods resulted in higher protein recovery (19.6 +/− 0.33%) compared to PEF alone (10.8 +/− 0.37%) and EAE alone (9.7 +/− 0.42%) (Steinbruch et al., 2023). Another study used PEF combined with mechanical pressing to extract proteins from the green macroalgae *Ulva* spp. and found a 7 times increase in total protein extraction compared to osmotic shock extraction (Robin et al., 2018). For the selective and efficient recovery of water-soluble proteins from *A. platensis* suspensions during water extraction, PEF combined with high-shear homogenization was applied (Carullo, Donsì, Ferrari, & Pataro, 2021). It is also worth noting that DES can be used in combination with other methods for plant protein extraction, such as high voltage electrical discharges, microwaves, sequential ultrasound, etc. The combination of DES with microwave technology has been reported to improve protein extraction and functional properties such as water/oil retention, emulsification, digestibility, solubility, gelling, and foaming (Olalere & Gan, 2023). Using the combination of

enzymes followed by alkaline extraction, Naseri, Marinho, Holdt, Bartela, and Jacobsen (2020) extracted up to 90% of protein content. More research is therefore required to determine the most suitable conditions for plant protein extraction, investigate the optimal combination of extraction methods, minimize economic costs, develop more environmentally friendly extraction methods, and increase the utilization of plant materials.

3. Structure and functional modification of plant proteins by emerging food processing technologies

3.1. Challenges and limitations of plant proteins

The applications of plant-based proteins are limited by a series of factors including poor water solubility, high complexity, and sensitivity to pH, ionic strength, and temperature. In addition, the allergenic components and unpleasant flavors of plant proteins also need to be improved. For example, vacuolar protein, β-conglycinin, and glycinin are the major allergenic substances in soybean, whereas ω-5 gliadins, α-amylase inhibitors prolamins, profilins, and glucoproteins are allergenic components in wheat proteins (Hadidi et al., 2022). Plant proteins may have unpleasant flavors such as "grassy", "green", "beany", "fatty", and "bitter" which can affect the overall organoleptic characteristics and consumers' acceptability (Leonard, Zhang, Ying, & Fang, 2023). Such off-flavors originate from volatile (e.g. alcohols, aldehydes, acids, ketones, alkanes) and non-volatile (e.g. peptides, saponins, phenolic compounds) substances present in the plant matrix. Unpleasant flavors may also be produced during extraction and processing. Furthermore, numerous anti-nutritional factors including saponins, enzyme inhibitors, lectins, oxalic acid, phytic acid, gossypol, raffinose, tannins, alkaloids, and hydrogen cyanide are present in the plant matrix and may remain on protein molecules during extraction process (Duraiswamy et al., 2023). These factors affect human health by interfering with nutrient absorption and uptake through chelation and enzyme inhibition. Therefore, suitable methods must be adopted to modify the characteristics of plant proteins, improve their functionality, eliminate allergenic substances, remove unpleasant flavors, reduce anti-nutritional factors, and meet the specific needs of applications. Generally, physical, chemical, and biological methods are used to modify proteins (Fig. 4). Recent studies on the modification of plant proteins using these three approaches are listed in Table 1. In fact, the novel protein extraction methods mentioned in the first part can also be used for protein modification.

3.2. Physical modification

Physical modifications include both thermal and non-thermal techniques. Thermal methods are mainly composed of extrusion, ohmic heating, microwave heating, radiofrequency treatment, and infrared irradiation. Meanwhile, non-thermal techniques consisted of high-pressure treatment, ultrasound, ultrafine grinding, cold plasma, and pulsed electric field (Fig. 4). The spatial conformation of proteins plays a crucial role in properties and structural functionalities. Under thermal techniques, polypeptide chains unfold, resulting in exposure of reacting sites and thereby changing nutritional and tech-functional properties of plant proteins. Ohmic heating facilitated covalent binding between soy protein isolate and catechin and has been applied in antioxidant film preparation (Wang et al., 2023).

As a non-thermal technique, ultra-high-pressure homogenization technology is used to compress the material by the static pressure of a liquid medium. It prevents thermal degradation and loss of bioactive components, making it suitable for protein extraction from foods with heat-sensitive components. Nevertheless, the extremely high static pressure could act on the non-covalent bond of the protein, change the spatial structure, and even cause protein denaturation. For example, Liu and Kuo (2016) found that high pressure (100 MPa) altered protein-

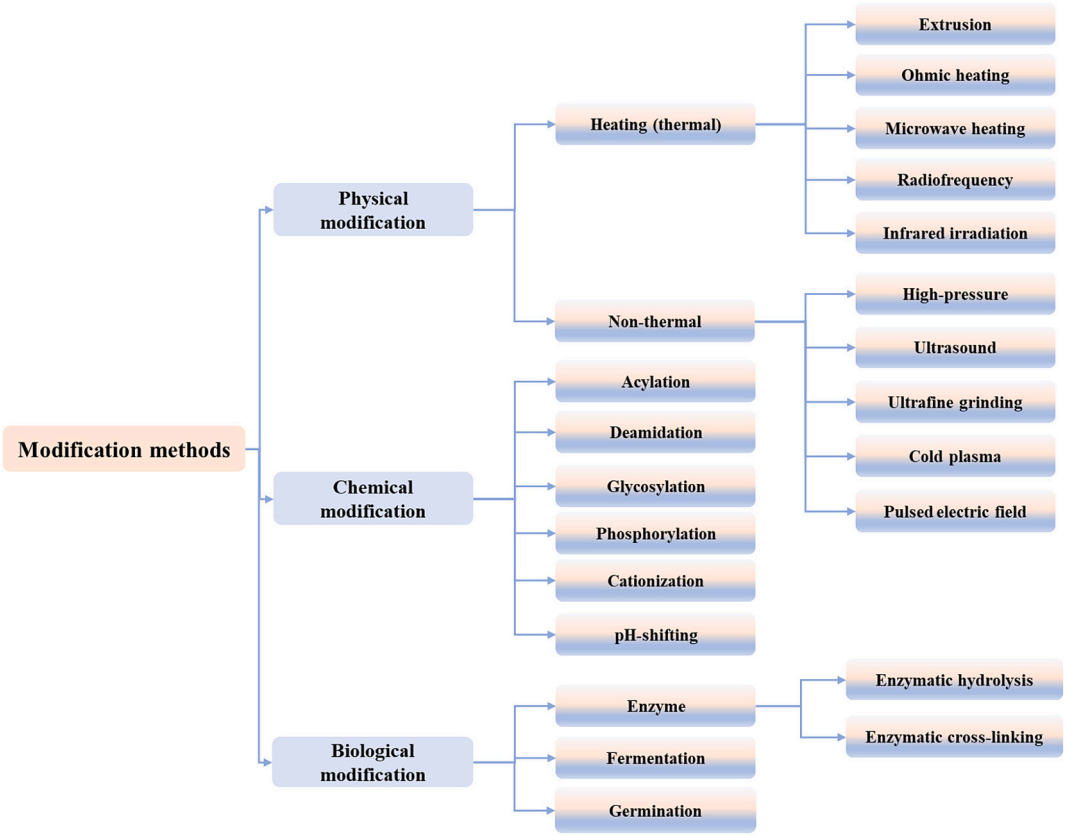

Fig. 4. Physical, chemical, and biological modification methods.

Table 1
Recent studies on the modification of plant proteins using physical, chemical, and biological methods.

Modification method		Plant-based protein matrix	Conditions	Main results	References
Physical modification	High-pressure homogenization	Lupin protein	pH 5 and 9, 25–200 MPa.	Reduced particle size (pH 5, pH 9, 25–100 MPa); Increased solubility (pH 5, and pH 9); highest viscosity (~10 Pa.s) (200 MPa, 10 passes); improved gelling properties and loss of modulus (pH 5, pH 9, 200 MPa).	(Lo, Kasapis, & Farahnaky, 2024)
	High-intensity ultrasound	Guamuchil seed	20 kHz; 200, 400, and 600 W for 15 and 30 min.	Reduced apparent viscosity and most significant shear thinning behavior (200 W and 600 W); modified inter- and intramolecular interactions.	(Flores-Jiménez et al., 2023)
	Microwave-vacuum dehydration	Pea protein	100 W/g microwave energy and 200 Torr vacuum-level for 2.5 min (250 J/g specific energy).	Reduced ($p < 0.05$) raw/pea and green/grass flavors; weak lamb/capric acid notes; increased ($p < 0.05$) chalky taste (5% pea protein non-dairy drink).	(Pratap-Singh, Yen, Singh, & Kitts, 2023)
	Pulsed electric field	Foxtail millet (*Setaria italica*) prolamin	Pulse voltage (5–3000 V), pulse width (10 μs–999 ms), pulse interval (100 ms–10 s), and pulse number (1–99).	Altered spatial conformation of millet prolamin; increased hydrophobicity and solubility in alcoholic solution; increased soluble aggregates and protein particle size; increased β-sheet content and the number of disulfide bonds; decreased α-helical content; ordered protein structure.	(Zhang, Sani, et al., 2023)
Chemical modification	Cold plasma	Peanut	Resonant frequency (52 kHz), discharge voltage (32 kV), duty cycle (118 s), discharge frequency (1 kHz).	Reduced solubility; altered allergenic structure (Ara h 1 and Ara h 2); reduced antigenicity.	(Venkataratnam, Cahill, Sarangapani, Cullen, & Barry-Ryan, 2020)
	Acylation	Pea protein isolate	At 0.3 or 0.6 g of Acetic anhydride or succinic anhydride per g protein in 10 wt% protein concentration, pH 8.	Improved oil holding capacity, emulsion properties, and gelation properties.	(Shen & Li, 2021)
	Deamidation	Rice protein	Alkaline deamidation (0.5 h, 343 K, and pH 11).	Improved stability for high internal phase emulsions (60 days); great potential as a saturated fat replacer.	(Vidotto et al., 2024)
	pH-shifting	Rice protein isolates	Protein solution (pH 1.0, 2.0, 3.0, 10.0, 11.0, and 12.0) was adjusted with the HCl (2 M) and NaOH (2 M).	Smaller emulsion particle size (alkaline pH change vs. acidic pH change); uniformed emulsion particle size distribution (pH 10).	(Shen et al., 2023)
	Phosphorylation	Rice bran protein	Different pH values (3.0, 5.0, 7.0, 9.0 and 11.0).	Altered the secondary and/or tertiary structure; improved solubility and emulsification activity; highest solubility and emulsification activity (pH 9.0).	(Hu, Qiu, Sun, Xiong, & Ogra, 2019)
	Maillard conjugates	Sesame protein hydrolysate	Sesame protein hydrolysate and gum Arabic via a wet heating approach with variable times (1, 3, 6, and 12 h).	Better partial unfolding and solubility/thermal stability; slowed release of anthocyanin (in vitro digestion); higher retention of anthocyanins [35 °C, 90 days storage, conjugate (93.13%) vs. unencapsulated powder (39.76%)].	(Parandi, Mousavi, Assadpour, Kiani, & Jafari, 2024)
	Enzyme hydrolysis	Lentil and chickpea protein isolates	Trypsin, varying levels of hydrolysis (5%, 10%, 15%, and 20%).	Increased solubility and oil-holding capacity; maintained emulsion stability (pH 7.8); decreased emulsion stability (pH 4.5); decreased water-holding capacity (chickpea protein isolates); decreased amount (lentil protein, from 55% to 32%); increased quality (chickpea protein isolate, from 55% to 60%).	(Thirulogasundar et al., 2024)
	Enzyme hydrolysis and fermentation	Pea protein isolate	Different proteolytic enzymes (papain, Esperase®, trypsin) and lactic fermentation with *Lactobacillus plantarum*.	Increased protein solubility and foaming capacity; reduced pea characteristic off-flavors; increased bitterness (Esperase® treatment).	(Arteaga et al., 2022)
Biological modification	Fermentation	Soybean, sweet potato, and Zanthoxylum pericarpium residues	*Ganoderma lucidum* fermentation.	Increased nutrient contents; increased active substances, amino acids, metabolites, and antioxidant activity (soybean residue and sweet potato residue); decreased content of bioactive substances, amino acids, and antioxidant activity (Zanthoxylum pericarpium residue).	(Cen et al., 2024)
	Fermentation	Chickpeas and Kamut	*Lactococcus lactis* fermentation.	Increased phosphorus and calcium concentrations; reduced cotton seed sugar levels (lactobacillus fermentation vs. spontaneous fermentation).	(Mefleh et al., 2024)
	Germination	Sesame protein	Germination treatments (0 d, 2 d, and 4 d).	Increased content of free sulfhydryl groups and surface hydrophobicity. Hydrolyzed high molecular weight proteins; improved functional properties and in vitro protein digestibility; altered thermal properties.	(Di et al., 2022)

protein rearrangements in soybean flour. The distribution of the acidic subunit of 11S and the alpha subunit of 7S was altered, resulting in the formation of poorly soluble particulate proteins. Therefore, parametric conditions require to be optimized to ensure that the physiological or technological function of the protein is not adversely affected. In addition, numerous studies have been carried out on the improvement of the techno-functional properties of proteins by UAE. Sun, Yu, Wang, Lv, and He (2021) observed an improvement in extraction rate, oil absorption capacity, proteolysis, and foaming properties of rice bran protein. Purdi et al. (2023) found an increase in water retention capacity, emulsification stability, foaming capacity, and stability of spirulina protein produced using UAE. An enhancement in emulsification properties by UAE was also found by Sun, Zhang, Zhang, Tian, and Chen (2020). Ultrafine grinding is also a non-thermal processing technique for the food functional properties modification. Ultrafine powder usually exhibits better adsorption and solubility than normal powder. It refers to the use of mechanical or fluid power to overcome the aggregation force within the solid itself to break it, resulting in large pores in the material and surface area increasing. After ultrafine grinding, powder has better physical and chemical properties.

3.3. Chemical modification

Chemical modification means the use of chemical reactions to modify specific functional groups of proteins or their molecular structure to enhance their biological activities and properties such as solubility, emulsification, and foaming. It mainly includes acylation, deamidation, glycosylation, phosphorylation, cationization, and pH-shifting (Fig. 4).

During acylation, protein amino groups are converted to amides. Depending on the acylating agent and amino/hydroxy group, they can be classified as succinylation, acetylation, and methylation (Shen & Li, 2021). Nucleophilic substitution reactions between nucleophilic groups in proteins and anhydrides introduce negatively charged acyl groups, which increase the surface static negative charge, weaken protein intermolecular interactions, and stretch the molecular structure (Shilpashree, Arora, Chawla, Vakkalagadda, & Sharma, 2015). Succinimidylation is an effective method to improve the thermal stability of proteins. Previous studies have found that succinylated rapeseed isolates at 5% showed better water holding, thermal stability, mechanical properties, and barrier properties (He et al., 2019). Another study used acetylation to modify pea proteins and found that acylated pea proteins showed significantly improved oil-holding capacity, greater water-holding capacity, higher emulsification capacity, and stability compared to unmodified proteins. However, modified pea proteins had reduced in vitro gastrointestinal digestibility (Shen & Li, 2021).

Deamidation improves the functional properties of food proteins by increasing the negative charge on the protein surface (Vidotto, Galvao, Tavares, & Hubinger, 2024). It converts amide groups in glutamine and asparagine residues to carboxyl groups. Deamidation modifications are mainly classified into physical deamidation, chemical deamidation, and enzymatic deamidation (Yang, Meng, Wu, Chen, & Xue, 2023). Compared with chemical and physical deamidation, enzymatic deamidation has the benefits of high specificity, great efficiency, a gentle environment, and security. The commonly used enzyme is glutaminase, which has been successfully employed to alter a variety of plant proteins such as rice bran protein, pea protein, glutenin, and soybean protein (Fernando, 2022).

Glycosylation, also known as the Maillard reaction, is a sugar conjugation reaction between polysaccharides and proteins. Carbohydrate molecules can be attached to amino acid side chains or lysine residues at the N-terminus of proteins, thereby altering the functional properties of proteins, including water retention, solubility, foaming and emulsification properties, texture properties, gelling ability, antioxidant properties, antibacterial activity, thermal stability, etc. (Feng et al., 2023). Glycosylation is generally affected by reaction time, temperature, pH, water activity, sulfites, and the number of amino compounds and carbonyl groups available during the reaction. Zhang et al. (2022) prepared soybean isolate protein-galactose conjugates by the melamine reaction and found that the melamine reaction changed the secondary structure, amino acid composition, and fluorescence spectra of soybean isolate proteins, and the structural changes were related to the content of D-galactose in the reaction.

3.4. Biological modification

Biological modification is mainly composed of enzymatic treatment, fermentation, and germination (Fig. 4). As discussed above, enzymatic treatment can improve the recovery of plant proteins. Simultaneously, as an environmentally friendly modification method, it can also reform certain functional characteristics of plant proteins. For example, Shuai et al. (2022) utilized four proteolytic enzymes including flavourzyme, neutrase, alcalase, and trypsin to hydrolyze pea protein, leading to the improvement of foaming and emulsification perspective after enzymatic treatment. In another study, either alcalase, novozyme, or flavourzyme was used to hydrolyze lentil protein concentrate, resulting in significant improvement of solubility (Vogelsang-O'Dwyer et al., 2023). Furthermore, enzymatic treatment also plays an important role in reducing bitter flavors and ameliorating allergies to plant proteins. Cuadrado et al. (2023) applied pressured heating and enzymatic hydrolysis to reduce peanut allergenic reactivity. Meanwhile, enzymatic treatment can also be applied in the production of bioactive peptides, such as antioxidant peptides, antihypertensive peptides, antibacterial peptides, and anti-inflammatory peptides (Tawalbeh, Al-U'datt, Ahmad, Ahmad, & Sarbon, 2023). Enzymatic hydrolysis cleaves peptide bonds in proteins to produce short-chain peptides, amino acids, or cross-linked polypeptide chains with lower molecular weight proteins. Some parameters of enzyme treatment impose limitations on their use, such as enzyme stability, reaction rate, ionic composition, temperature, enzyme concentration, and pH. For instance, Dent et al. (2023) found that hydrolysis improved the solubility of plant proteins, but it simultaneously caused aggregation because of structural changes. Enzymatic digestion may also introduce a bitter flavor that requires further processing to remove.

Fermentation is also considered to be an effective biological method for improving functional properties, increasing bioavailability, producing bioactive peptides, and expanding the range of plant protein utilization. Lactic acid bacteria (e.g. *Lactobacillus*, *Staphylococcus*, *Enterococcus*, *Micrococcus*, etc.) and certain fungi (e.g. *Candida* spp.), are mainly used to ferment plant-based proteins (Ter et al., 2024). During the fermentation process, the fermenter produces proteases and peptidases that cleave proteins into peptides and finally hydrolyze them into amino acids. Xu et al. (2022) used lactic acid bacteria to obtain natural antioxidant peptides and developed antioxidant fermented milk. Mefleh et al. (2024) reported that the allergic content of cotton seed sugar was significantly decreased after fermentation with *Lactococcus lactis*. The combination of enzymatic hydrolysis and fermentation has great potential for treating allergenic components, improving solubility, and increasing bioavailability. Pontonio et al. (2020) used protease and xylanase enzymes as well as lactic acid bacteria for hemp seed processing and found antioxidant peptide release and protein digestibility increase. Arteaga et al. (2022) combined different enzymes and *Lactobacillus plantarum* fermentation to treat pea isolates and observed increased protein solubility, improved foaming capacity, and decreased characteristic off-flavors.

Germination is also a widely utilized biological method to improve the nutritional and tech-functional properties of plant proteins. During germination, higher molecular weight proteins and starch are broken down as proteases and amylases are activated (Di et al., 2022). This changes the nutritional and tech-functional properties of the proteins, making them more suitable for food applications. In addition, germination removes or reduces anti-nutritional factors, increasing protein

digestibility and bioavailability. A previous study has found that germination increased free sulfhydryl groups and surface hydrophobicity, improved functional properties and in vitro protein digestibility, and changed the thermal properties of sesame protein (Di et al., 2022). Abdelbost, Bonicel, Morel, and Mameri (2024) reported that germination reduced protease inhibitors, phytic acid, and tannins.

3.5. Comparison of common modification methods

Physical modification, which neither introduces chemical reagents nor requires high cost, is suitable for industrial production. However, traditional physical methods, such as heat treatment, high-speed stirring, and extrusion treatment, can lead to permanent denaturation or aggregation of plant proteins, loss of secondary and tertiary structure, and impairment of nutritional and organoleptic properties (Nasrabadi et al., 2021). Novel physical treatment techniques including ultrasound, microwave, high-pressure treatment, radiofrequency treatment, cold plasma, and pulsed electric fields are considered to be emerging high-potential novel physical modification methods for the future(Lo et al., 2024). These methods have produced significant structural and functional modifications of plant proteins. They can better achieve the goals of sustainability, feasibility, consumers' acceptance, and use of renewable resources than other techniques. Compared to physical and biological approaches, chemical modification is currently the least-used technique. Chemical modification, such as the Maillard reaction, can bring pleasant flavors and colors to food products. Nevertheless, it is still concerned with environmental pollution, recycling difficulties, chemical residues, and high production costs. In addition, it demands specialized knowledge to end the reaction for optimized results. Biological modification has many advantages over chemical methods, such as environmental friendliness, low energy consumption, reduced use of harmful chemicals, and mild conditions. They can improve digestibility and techno-functional properties, reduce intrinsic allergenicity, as well as produce value-added products with health-beneficial properties. However, some enzymes are expensive, unstable, and require strict reaction conditions. In conclusion, the choice of modification method must be fully considered according to the actual experimental purpose, raw material characteristics, economics, or feasibility.

4. Application of plant proteins in the food industry

Plant proteins are used extensively in the food industry and have great benefits as well as potential. This section summarizes typical examples of the application of plant-based proteins in the food industry (Fig. 5, Table 2).

4.1. Food packaging films

Plant protein sources have received much attention due to their favorable mechanical and techno-functional properties such as cohesion/adhesion, edibility, biodegradability, renewability, and environmental friendliness (Santhosh et al., 2024). There are abundant sources of plant proteins for food packaging films, including corn, grains, wheat, cottonseed, peanuts, peas, soybeans, barley, mung beans, oats, quinoa, etc. These plant-based proteins are unique in their structure, with porous systems and superior flexibility, and contain hydrophobic and antioxidant proteins. Furthermore, they can form adhesive films that effectively protect food products inside the packages from the external environment (Zhang, Liu, Sun, Wang, & Li, 2020). Various techniques for producing plant protein films include solvent casting, compression molding, extrusion, and electrospinning. The functional efficiency of plant proteins in food packaging is enhanced by the addition of various additives or natural polymers such as nanomaterials, plasticizers, preservatives, bioactive compounds, etc. (Bremenkamp & Sousa-Gallagher, 2024). Protein-based usable films have been used in the packaging of fruits and vegetables, dairy products, meat products, and frozen foods (Zhang, Jing, et al., 2023).

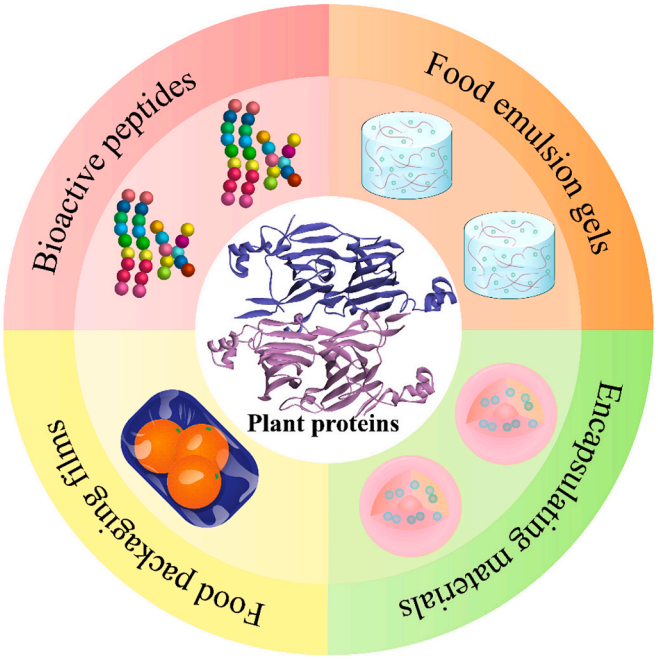

Fig. 5. Typical examples of applications of plant-based proteins in the food industry.

Recently, there has been a growing interest in the development of biopolymer films and coatings using plant proteins. Edible films/coatings can transport food-grade additives such as antioxidants, antimicrobials, preservatives, flavors, and fragrances, while also acting as selective barriers to prevent vapors, gases, and solutes from entering different food systems (Echegaray et al., 2023). These films can also be ingested with packaged/coated foods. However, since plant protein films are hydrophilic, their ability to block moisture and water vapor is low, limiting their development in food packaging (Liu et al., 2024). In addition, plant protein films usually require the addition of plasticizers (glycerol, polyols, sorbitol, polyethylene glycol, etc.), which leaves much to be desired in terms of safety. Finally, economics is also one of the issues to be considered for plant protein films.

4.2. Bioactive peptides

In addition to their nutritional value, peptides and protein hydrolysates from plant sources have a multitude of physiological functions such as antihypertensive, hypolipidemic, hypocholesterolemia, antioxidant, antibacterial, antifungal, immunomodulatory, anticancer, antidiabetic and anti-obesity effects (Chen, Ning, et al., 2021). Bioactive peptides can be extracted from a variety of plant protein sources including legumes, seeds, grains and pulses, and olive residues (Hou et al., 2023). Bioactive peptides are characterized by high biological activity, low toxicity, and easy metabolism in the human body, which has led to interest in food-derived bioactive peptides as potential components of health-promoting functional foods for the treatment of diet-related chronic diseases.

Bioactive peptides can be released from proteins by in vivo digestion or by protein hydrolysis during processing (e.g. fermentation, enzymatic degradation). For example, one study used enzymatic hydrolysis to obtain antihypertensive, antithrombotic, and antioxidant peptides from amaranth proteins (Ayala-Niño et al., 2022). Another researchers have obtained antioxidant peptides and hypoglycemic peptides from soy protein hydrolysates (Xu, Sun, et al., 2023). In addition, Ajayi, Mudgil, Gan, and Maqsood (2021) found that amaranth protein-derived peptides have cholesterol esterase and pancreatic lipase inhibitory activities.

Table 2
Recent studies on the application of plant-based proteins in the food industry.

Source	Extraction method	Protein treatments	Potential use in food	References
Zein	_	_	Food packaging films for prolonging the shelf life of Agaricus mushrooms	(Zhang et al., 2020)
Pea protein isolate	_	Atmospheric cold plasma treatment	Edible films for food packaging	(Santhosh et al., 2024)
Rice dreg protein	Alkaline protease	Angling method enrichment	Antioxidant peptides	(Chen, Chaihu, et al., 2021)
Soy protein isolates	Alkaline extraction	Five enzymes (alcalase, pepsin, trypsin, papain, and bromelain)	Antioxidant peptides and hypoglycemic peptides	(Xu, Sun, et al., 2023)
Pea protein isolate	_	Emulsion/acidification technique	Embedding probiotics as wall material in microcapsules	(Ismail et al., 2023)
Raw chickpeas and nuts	_	_	Plant-Based Cheese Snack	(Nie et al., 2023)
Pea protein	Dry fraction	Emulsion method	Spreadable plant-based cheese analogue	(Mefleh et al., 2022)
White chia seed protein, buckwheat protein, and pea protein	_	Spray-drying microencapsulation	Microencapsulation of blackcurrant and cocoa polyphenols	(Hoskin et al., 2023)
Silkworm Thorn (*Cudrania tricuspidata*) Fruit	Ethanol precipitation	Enzymatic Hydrolysis	Plant protease for producing human-grade protein hydrolysates	(Yang et al., 2024)
Red lentil protein isolate	Aqueous extraction	Fermentation	Antifungal peptides	(Tonini et al., 2024)

Hydrolysis conditions (pH, temperature, and time), type of hydrolase, degree of hydrolysis, and substrate/enzyme ratio are the main factors influencing the function of bioactive peptides. Several pretreatment processes such as microwave, pulsed electric field, ultrasound, high-pressure homogenization, and heating can be used for modification to enhance the bioactivity of peptides (Cabanos et al., 2021).

Recently, various peptides have attracted interest in food applications. The development of peptide-rich infant formulas, functional foods, and nutraceuticals is increasing since peptides are easily absorbed and are particularly beneficial to groups with special nutritional needs such as infants, young children, exercisers, and the elderly. Several products containing bioactive peptides have appeared on the market, including solid beverages, lyophilized powders, oral liquids, and special diets. For example, drinks containing bioactive peptides (complex peptides, soya peptides) have been successfully marketed. Bioactive peptides from barley grain proteins can be added to food supplements or protein mixes for sports enthusiasts (Tok, Moulahoum, Kocazorbaz, & Zihnioglu, 2021). Allergenicity, toxicity, bitter issues, bioavailability, and thermal instability of plant-derived peptides need to be addressed. Therefore, appropriate modification methods and encapsulation technology should be employed.

4.3. Food emulsion gels

Emulsion gels combine both emulsion and gel properties and are structured emulsion systems that appear as soft, solid materials. Based on morphological properties, they can be classified into three types: fluid emulsion gels, emulsion gel particles, and bulk emulsion gels. Among them, fluid emulsion gels include gel-like Pickering emulsions and broken emulsion gels (Yiu et al., 2023).

Widely used in the food industry, emulsion gels can improve emulsion stability and enhance rheological and nutritional properties of hydrogels. Plant proteins from soybean, pea, corn, black bean, chia seed, and oats have been used in emulsion gel formulations as fat replacers, bioactive encapsulants, and functional materials (Xu, Yang, et al., 2023). Emulsion gels have low-fat content, and high-quality organoleptic properties, and can be used in meat products, dairy products, baked goods, functional foods, and edible 3D printing inks (Li, Wang, Ying, Huang, & Hayat, 2024). For example, studies by Lingiardi, Galante and Spelzini (2023) have shown that quinoa protein hydrolysates have the potential to be used in emulsion gel formulations and can be applied in soft solid foods. Another study used a plant protein-polysaccharide complex gel-like emulsion to encapsulate lycopene (Lin, Kelly, and Miao, 2021). Choi, Choi, Kim, Hahn, and Choi (2023) prepared emulsion gels for mimicking animal adipose tissue using soybean oil, soybean isolate protein, agar, and alginate.

However, product development of emulsion gels is a great challenge, because although they have the potential to be healthy alternatives to conventional fats, their potential has not yet been fully realized. On the one hand, the poor solubility and emulsification properties of plant proteins, the presence of allergenic components as well as bitter and anti-nutritional components need to be improved by suitable modification methods. On the other hand, further research is needed to expand the use of plant-based emulsion gels in food applications.

4.4. Encapsulating materials of bioactive compounds

Food contains various active ingredients, such as flavors, nutrients, unsaturated fatty acids, pigments, probiotics, etc. Protection is required during food processing and storage to maintain its quality and shelf life. Microencapsulation is a promising technological process to protect bioactive compounds from harsh storage, processing, and gastrointestinal conditions. There are several key benefits to use microencapsulation technology, including (1) enhanced stability; (2) controlled release; (3) ease of handling and precision; (4) taste, color, and odor masking; (5) prevention of interactions within different components of a formulation (Hoskin, Grace, Xiong, & Lila, 2023).

Microcapsules can be simply regarded as composed of core materials and wall materials, the core materials are mainly bioactive substances, components that are not easy to store, or substances that have adverse effects on other components (Ismail, Lim, Lim, & Ramasamy, 2023). Commonly used wall material substances are proteins, vegetable gums, cellulose, condensates, oils, inorganic salts, etc. (Lei & Lee, 2024). These wall materials can be used alone or in blends. They can also be added to some plasticizers, surfactants, pigments, and other modifiers to improve quality (Silva, Gonçalves, et al., 2023). In the food industry, the selection of wall materials needs to be based on the viscosity of the product, permeability, hygroscopicity, solubility, clarification, and other factors, and requires non-toxic, non-smell, no adverse effects on the core materials (Sun et al., 2023). Spray drying, emulsion, extrusion, electrospinning, and coacervation are popular encapsulation technologies for food actives (Zhao, Liu, et al., 2023). As unique carriers, plant proteins can effectively encapsulate unstable and highly active compounds. The most common plant proteins like soybean protein isolates, pea protein isolates, rice protein, sunflower protein, oat protein, legume protein, and wheat cereal protein act as cladding in encapsulation (Islam et al., 2023). The mentioned plant protein isolates are used in the food industry not only for their encapsulating ability but also because of their

low cost, high nutritional value, and excellent emulsifying and gelling properties.

There have been numerous studies by scholars at home and abroad on the use of microencapsulation technology for bioactive substances. Plant proteins have been reported to be used for encapsulation of probiotics, micronutrient packs, food additives, essential oils, active peptides, and functional proteins (Table 2). According to Wu et al. (2022), soybean isolate protein was modified with tannic acid to provide a perfect wall material for essential oils. Quinoa proteins, lentil proteins, soy proteins, and sodium caseinate were also applied as carrying materials to encapsulate bioactive compounds from annatto seed extract by ionic gelation (Quiroz et al., 2020). Pea protein isolate, soy protein isolate, brown rice protein, hemp protein, and sunflower protein have been reported to be suitable as wall materials for spray-drying microencapsulation of sunflower oil (Le Priol et al., 2019).

5. Conclusion and prospect

Novel extraction methods (e.g. ultrasound-assisted extraction, pulsed electric field, deep eutectic solvent, enzyme-assisted extraction, and combined methods) offer greater advantages over traditional plant protein extraction methods (alkaline extraction, acid extraction, and salt extraction), such as environmental friendliness, low energy consumption, and fewer toxic residues. Since there are some challenges associated with plant proteins, such as bitter flavors, anti-nutritional factors, allergenic components, poor solubility, etc., suitable modification methods are required to improve their functional properties and remove undesirable factors. Physical modification, chemical modification, and biological modification are among the many methods that have been used to modify plant proteins. It is important to investigate suitable processing and modification conditions as this contributes to optimizing the functional performance of plant proteins. In fact, it has become a trend to use plant proteins instead of animal proteins in the food industry as food packaging films, active ingredient encapsulation materials, food emulsion gels, bioactive peptides, etc.

In the future, the development, identification, efficacy, and application of plant proteins should be explored. It is important to identify the main factors affecting the physicochemical stability of different types of plant proteins to optimize their performance for specific applications. In addition, the field of application for these plant proteins should be broadened. For instance, their application in drug delivery and in the manufacture of functional foods, etc., aimed at treating or preventing certain diseases through diet, should be considered.

CRediT authorship contribution statement

Jiayue Tang: Software, Investigation, Formal analysis, Data curation, Conceptualization. **Dan Yao:** Resources, Investigation, Formal analysis. **Shuaibo Xia:** Investigation, Formal analysis, Data curation. **Lingzhi Cheong:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Funding acquisition, Formal analysis, Conceptualization. **Maolin Tu:** Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

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

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