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UNLOCKING THE POTENTIAL OF PLANT-BASED PROTEINS

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Abstract:

Consumers' demand for plant-based protein (PBP) products is increasing and is expected to double by 2050. Several factors drive this trend including potential health-promoting characteristics of PBPs, growing consumers' awareness of the risks associated with diets high in animal proteins (e.g. saturated fats), the need for environmentally sustainable food production, ethical concerns about animal welfare, and perception of protein as a "positive" nutrient. PBPs are cost-competitive and ecologically sustainable alternatives to animal-based proteins (e.g. egg, meat, dairy). Despite their promise, the nutritional quality of PBPs may be inferior to animal proteins. Research has been done to inquire about the functional characteristics of PBP sources but there is a dire need to analyze the challenges related to functional characteristics and extraction of proteins from plant sources. Therefore, this review aims to present extraction processes and technologies, characteristics, and functional properties of PBPs. Strategies to functionalize PBPs are discussed. This review presents the potential applications of PBPs as edible coating materials for vegetables and fruits, and sources of bioactive peptides for nutraceutical and therapeutic products. Additional applications include nondairy alternative products like yogurt, meat analogs and 3D food printing, synthesis of nanoparticles, bioplastics and packaging films are the best known PBPs-based products. It highlights current trends and challenges making it timely and pertinent to the food industry and researchers. This review article further highlights challenges such as food safety risks from hazardous plant sources, allergens, and health concerns. These findings aim to guide the food industry and regulatory authorities in identifying trends, addressing risks, and prioritizing future research to ensure safe and sustainable food production for everyone.

Keywords: plant-based proteins, functional properties, health effects, side effects, industrial applications, extraction technologies.

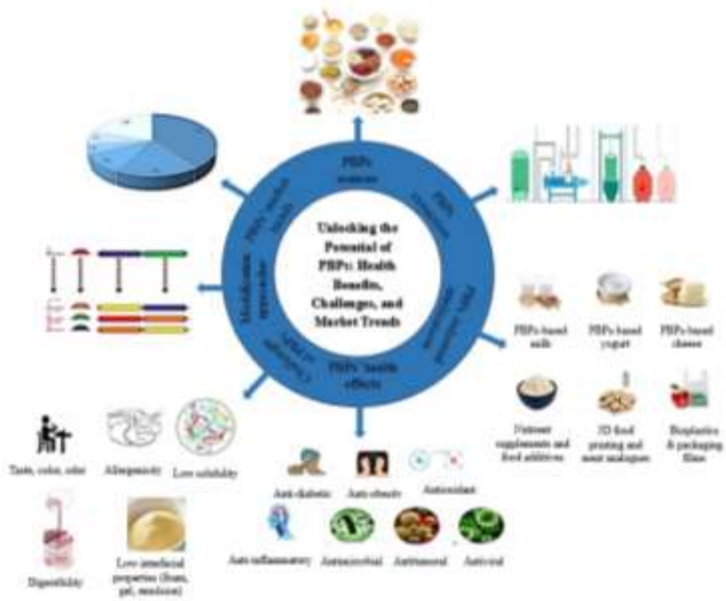

Figure 1: An overview of plant-based proteins; their health benefits, challenges, and market trends

1. Introduction:

The world population is assumed about 9.7 billion by 2050 (Samad et al., 2024a, Samad et al., 2024b, Samad et al., 2024c, Samad et al., 2025) so, problems related to enough food availability along with food safety and security have to be overcome, while at the same time keeping agricultural practices with environmental limits and accountable reduce in greenhouse gas (GHG) emissions. Our food industry is in charge of factors like malnutrition and inadequate food for the mass population (Saxena, 2018). Traditionally, meat and other dairy products have been important for protein in human diets. Proteins play major roles in our body such as serving as catalysts, providing mechanical support and helping in immune responses, transmitting nerve impulses, transporting and storing oxygen molecules, generating motions, making enzymes, and aiding growth and differentiation (Gurusamy et al., 2024). PBPs such as milk, meat, and eggs are given to animals to produce animal-based proteins. This process is inefficient as it produces only around 3% of animal proteins from plant proteins (Rashwan et al.,2023). Direct PBP production from protein-rich plant sources can solve this problem. These include lentils, soybeans, wheat, nuts, pinto beans, chia seeds, sorghum, and quinoa which can be used to produce protein-rich food (Kumar et al., 2022). These products include plant-based meat (artificial meat), bioplastics, non-dairy milk products (cheese, yogurt, beverages), nutrient supplements, and others (Kumar et al., 2022). Therefore, the use of PBPs in diets is significant as they are enriched with nutritional components such as phenolic compounds, fibers, anthocyanins, catechins, etc. As a result, several antioxidants, anticancer, anti-obesity, antidiabetic, and others can be found in PBP products (Rashwan et al., 2023).

In older adults, there is growing clinical shreds of evidence supporting the therapeutic potential of proteins at the level of dietary plant-based protein administration recommendations. These benefits include lean body mass (Rashwan et al., 2023; Kumar et al., 2022; Gurusamy, 2024), improved bone density (Rashwan et al., 2023; Agostini et al., 2018), gait speed (Kumar et al., 2022), and anti-inflammatory agents 8. Requirements of PBPs have increased significantly over the last few years. The world protein market reached 38 billion USD in 2019 and the expected growth rate is 15.4% by 2030 as shown in figure 2. The increase in vegetarian, vegan, and flexitarian communities has fueled the utilization of PBPs in human diets. Overall increase in the population and food demand propelled the protein market and replacer protein ingredients (Frezal et al., 2022). Furthermore, food security and, the preservation of natural resources are global concerns because population growth, climate change, and changing diets need to be addressed. Consumers are paying attention to sustainability and transparency in the food supply chain (Hanjra & Qureshi, 2010). Accordingly, the food industry is considering the commercialization of food products containing ingredients from environment-friendly crops (Helkar et al., 2016). Another important reason to choose PBPs is protein-based allergens. Soy and dairy products including Eggs are accompanying "big eight" food allergens that are approved by the Food and Drug Administration (FDA). Proteins have major functions in flavor enhancement, structure building, and stabilizing characteristics, researchers are trying to alternate synthetic proteins with functional proteins with several advantages especially high-value ones like encapsulation of flavors and bioactive compounds (i.e. fish oil) (Aimutis, 2022). Therefore, analysis of new vital potentials of PBPs is essential to replace the existing alternatives of proteins to their market eminence. Food industry owners are trying to gain knowledge about plant-based proteins to are rich in flavor, nutritional value, and functionality that will partially or replace traditional animal and plant proteins (Mkhize et al., 2024). There is the question about investigating effective protein extraction technologies to ensure high yield, development of cost-effective functionalization strategies, identify innovative applications, find ways to overcome the challenges associated with the flavor and texture of PBP products, secure an abundant supply of proteins, and explore the diversity of crops (Aimutis, 2022). This review provides comprehensive knowledge about protein-rich plants along with potential applications of PBPs for the product of food and food products. In this article, the health benefits and concerns of PBPs and their products have been discussed. Therefore, this context could be useful for gaining knowledge of plants rich in proteins and their related products that may be helpful not only to food workers but also food industrial revolution and public health authorities.

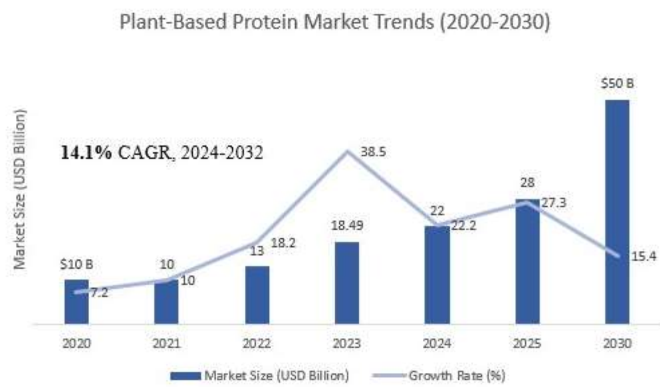

Figure 2: Plant-based protein market trends (2020-2030) (Market data forecast, 2024)

2.0 Plant-based protein sources:

Many PBP sources have lately been investigated to offer dietary protein and address the population's eating issues (Hughes et al., 2014). Certain important amino acids may be absent from PBPs, related to sources. Amaranth and quinoa are considered pseudo cereals, and have a considerable quantity of lysine (Langyan et al., 2022; Rao & Poonia, 2023). Due to variations in soil types, climate, precipitation, geographic latitude and altitude, farming methods, and cultivars, the same plants can occasionally have varying nutritional levels (Liu et al., 2017). Humans have long utilized some plants, such as soybeans, peas, and beans, as sources of protein (Sa et al., 2020). Different PBPs are given below with their protein and amino acid content:

Plant/Crop	Amino acid content (%)														Protein content (%)	References
	Threonine	Methionine	Phenylalanine	Histidine	Lysine	Valine	Leucine	Isoleucine	Serine	Glycine	Proline	Alanine	Tyrosine	Arginine		
Soy	2.3	0.3	3.2	1.5	3.4	2.2	5	1.9	3.4	2.7	3.3	2.8	2.2	4.8	39.4-44.4	Sharma et al., 2014
Wheat	1.8	0.7	3.7	1.4	1.1	2.3	5	2	3.5	2.4	8.8	1.8	2.4	2.4	9.3-12.33	Sharma et al., 2014
Rice	2.3	0.3	3.7	1.6	4.7	2.7	5.7	2.3	3.6	2.8	3.1	3.2	2.6	5.9	5.8-11	Devi et al., 2015
Potato	4.1	1.3	4.2	1.4	4.8	3.7	6.7	3.1	3.4	3.2	3.3	3.3	3.8	3.3	7.9-8.0	Sharma et al., 2014
Lentil	3	0.8	4.5	2.5	7.3	4.5	7.8	3.8	3.5	3.6	4.9	4.7	3.3	7.6	10.5-36.4	Fouad and Rehab, 2015
Peanut	-	0.89-1.13	4.51-5.09	2.10-2.33	3.01-3.72	3.18-4.02	5.54-6.61	2.65-3.26	4.48-4.98	5.02-7.70	3.74-4.32	3.55-4.02	3.20-3.66	9.90-11.57	25-29	Latif et al., 2013
Cottonseed	2.9-3.1	1.3	4.7-4.9	2.6-2.8	4.2-4.6	4.2-4.6	5.2-5.6	2.8-3	3.8-4.1	3.7-3.9	3.8-4.1	3.5-3.8	2.5-2.7	9.3-10.2	38-45	Bertrand et al., 2005
Kidney bean	3.17-3.77	0.72-1.62	4.48-5.91	2.61-2.94	4.91-6.48	4.58-5.38	6.72-8.46	3.81-5.21	4.59-5.24	3.19-3.72	2.95-4.33	3.07-3.80	3.16-5.25	5.29-6.08	22.06-32.63	Kan et al., 2017
Lupin	1.6	0.2	1.8	1.2	2.1	1.4	3.2	1.5	2.5	2.1	2	1.7	1.9	5.5	39-55	Sharma et al., 2014
Corn	1.8	1.1	3.4	1.1	1	2.1	8.8	1.7	2.9	1.6	5.2	4.8	2.7	1.7	11-Sep	Sharma et al., 2014
Pea	2.5	0.3	3.7	1.6	4.7	2.7	5.7	2.3	3.6	2.8	3.1	3.2	2.6	5.9	23.1-30.9	Lam et al., 2018

Table 1: Amino acid and protein content of different plant sources

2.1. Legumes:

Legumes are referred to as the greatest valuable food because they are enriched in carbs, protein, energy, vitamins, minerals, and fiber (Kamboj & Nanda, 2018). A diet high in legumes has several positive health impacts on people's health (Conti et al., 2021). Soybean protein is thoroughly studied (Semba et al., 2021). Chickpea-based food items are the main source of high-end stuffed protein in foods. Peas and other highly nutritious legumes are incorporated into different food products to enhance protein consumption (Wang et al., 2010). Pigeon peas and their proteins contain sulfur and are safe for consumption (Adenekan et al., 2018).

2.2. Cereals:

Cereals such as rice, corn, and wheat are the most often consumed staple foods worldwide. Out of all cereal grains, rice is most frequently consumed worldwide. According to research that examined the amino acid composition of the proteins found in rice, globulin mostly contains amino acids that include sulfur, whereas albumin has the highest amount of lysine (Amagliani et al., 2017). Additionally, some research has been done to increase the yield of rice protein extracted using various isolation methods (Kumar et al., 2021). One study discovered that lysine is much less prevalent in rice protein isolates (Jayaprakash et al., 2022). A mostly nutrient-dense source of protein is millet and its protein concentrates. It often has a high concentration of lysine and other important amino acids. Cereal-based proteins' nutritional characteristics have also been widely utilized in baked goods and industrial uses. Bread items made with wheat flour and faba bean flour had higher levels of important amino acids during fermentation, according to research. The combination of grains and beans enhances the total nutritious value (Coda et al., 2017).

2.3. Pseudo-cereals:

The majority of dicotyledonous plants are regarded as false cereals or pseudo cereals, like quinoa (Nhamo & Talabi, 2024). The sources are in rich vitamins, fiber, minerals, unsaturated fatty acids, and high-quality protein. These sources also offer higher protein bioavailability and high-quality necessary amino acids. Besides these benefits, they are gluten-free so, important for celiac disease medication (Alvarez-Jubete et al., 2010). Quinoa and amaranth are enriched with lysine so, suitable for diet (Lopez et al., 2018).

2.4. Seeds:

A vital source of nutrients is the seeds. Consumption of foods produced from plants is steadily rising (Schmidt et al., 2023). In the amino acid content of chia seeds, lysine is not included, but arginine and leucine were discovered to be present in considerable amounts in watermelon seeds (Anaya et al., 2015; Langyan et al., 2022).

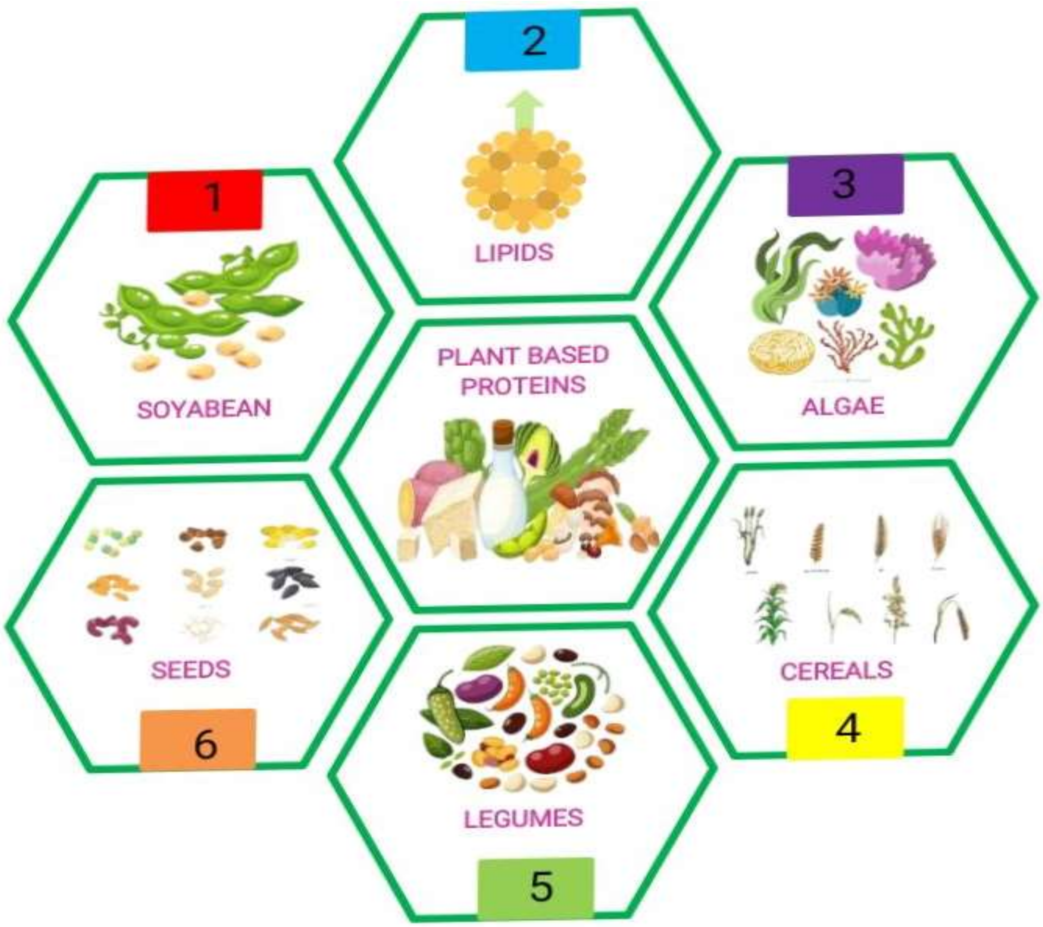

Figure 3: Plant-based sources of proteins

2.5. Almonds and Nuts:

Nuts and almonds are abundant in high-quality proteins, fatty acids, and lipids. Brazilian savanna's pequi and baru species are unusual almonds that contain proteins and amino acids in high quantity (de Oliveira Sousa et al., 2011). Bari contains all necessary amino acids but almonds only contain sulfur compounds. Lysine and valine are present in low concentrations in peanuts so, it is not considered a standard protein source (Sa et al., 2020).

2.6. Meat analogs from plant proteins:

Food sectors help manufacture good quality plant-based meat alternatives like ground beef, burgers, sausages, and nuts. Making goods that mimic the characteristics like texture, and taste of muscle fibers and connective tissues, is more difficult (McClements et al., 2021). In addition to nutritional content, meat analogs should ideally have sufficient structural resemblance. Plant macro-nutrients a few micro-nutrients and other components, such as minerals, vitamins, flavorings, colorants, preservatives, and binders, are the primary sources of meat analogs (Benkvic et al., 2023). For each beef product, the components and processing methods used to create these analogs should be improved. The surface of the meat analogs should have an opaque feel, comparable to that of actual flesh (Kyriakopoulou et al., 2021). The food industry has employed several strategies to sustain the color of plant-based meat substitutes. Meat replicates the proper color of meat by using juice extracted from beet, which contains betalain. Additionally, the food colors its goods using hemoglobin, which is derived from the roots of soybeans (Sha & Xiong, 2020). Structures of meat synthesized by plat-proteins that are closely related to the feel of actual meat are being sought for using a variety of scientific and technical techniques, such as physicochemical and processing methods (McClements et al., 2021).

2.7. Milk analogs from plant protein:

An accurate understanding of light scattering theory, particle reduction methods, and particle instability processes is necessary for valuable milk analog production. Two methods have been employed to produce milk analogs: homogenization (which includes mixing isolated plant-based components like emulsifiers, oils, and thickeners) and disruption of plant cells (Poul et al., 2020). Generally, the components and manufacturing techniques are adjusted to create milk analogs that reduce the beneficial and appealing properties of cows' milk (McClements et al., 2019).

2.8. Egg analogs from plant protein:

Eggs are used in different foods including paste, mayonnaise, baked products, and desserts, eggs can be boiled, fried, poached, or scrambled (Shidara et al., 2023). In general, plant-based egg analogs have to possess favorable physicochemical and functional characteristics. For instance, exactly like actual eggs, egg analogs ought to be able to functionally change a liquid into a colloidal solution when we heat it (McClements et al., 2021). The solution temperature of plant proteins employed in egg analogs ranges from 63 to 93°C, indicating that a greater temperature is required to replicate the texture and structure of actual eggs. Scanning calorimetry and shear rheometrics are used to gather data on protein denaturation and gelation temperatures (Soderberg, 2013).

3.0. Extraction technologies of protein:

Techniques for protein extraction are among the most crucial procedures that are needed for innovation. The need for eco-innovative approaches to improve protein extraction output without sacrificing environmental sustainability or the nutritional, technical, and functional qualities of proteins is urgent. To the best of our knowledge, polyphenols, fiber, lipids, and carbohydrates serve as the main structural links between proteins and other macromolecules in plants. The extraction process must be able to disintegrate cell walls and structural membranes, as well as break structural bonds, to release proteins efficiently. To do this, some studies looked into the standard extraction methods of using solvents, salt, and alkali (Bou et al., 2022). These traditional extraction methods can only successfully break down molecule structure, which means, that about half of the proteins found in a plant can be extracted (Venkateswara Rao et al., 2023). NaOH, KOH, NaHCO3, or NaCl in extraction did not improve the selective extraction of necessary amino acids (Cabral et al., 2022).

Several pre-treatment techniques are now being used to make protein extract easier. These include physical and enzymatic approaches in addition to some new extraction techniques like ultrafiltration membranes, deep eutectic solvents, and pressurized liquids (Zhao et al., 2023; Hernández-Corroto et al., 2020). Choline chloride-urea, choline chloride-oxalic acid, and choline chloride-glycerol are examples of deep eutectic solvents (DESs) that were created to extract protein from sea-buckthorn seed meal and contrasted with alkaline. According to findings, proteins with deep eutectic solvents had a greater total amino acid content, more β-turn, less β-sheet, and more essential amino acids. Additionally, to extract the protein from okara enzymatic pretreatment was used, which is the by-product of tofu and soy drinks. To facilitate protein extraction, viscozyme was used to hydrolyze the cell walls of okara, which contains a spectrum of carbohydrates (de Figueiredo et al., 2018).

3.1. Process:

Proteins from a variety of plants, including lupins, peas, lentils, and almonds (Maykish *et al*., 2021), have been extracted. There are several ways to generate protein isolates from plant-based flours, and they primarily rely on the raw substance and its very near makeup (Boye & Barbana, 2012).

Protein isolates that typically contain more than 80% protein and plant-based protein concentrate with varying protein contents (between 50% and 80% protein) are roughly categorized as either aqueous or dry fractionation. The first step is the oil extraction from raw substances with a high level of oil, like oilseeds and pulses. Membrane filtration, namely ultrafiltration, is typically employed in the last stage of extraction to concentrate the protein into an isolate or a concentrate, depending on the protein content. Notably, an extra step of acid precipitation of proteins at their isoelectric pH can be added to the manufacturing of the concentrate or isolate, and drying and concentration processes become easier (Berghout *et al*., 2014). Before the final protein extract can be achieved, these procedures are sometimes time-consuming and difficult. A few experts were working on dry fractionation, which entails milling the seeds and solvent extraction of oil followed by air classification, where the protein particles are separated from starch granules and husks in a cyclone-type separator, in light of the time-consuming steps involved in the aqueous extraction of proteins (Pelgrom *et al*., 2013). The cost of aqueous extraction is higher than that of dry fractionation because it requires many processing steps, but produces a better purity (45%–55% protein) than dry fractionation. Another drawback of aqueous fractionation is that the yield of protein is typically lower; therefore, concentration of the extract is required to augment this. Drying the extracts can increase their concentration, but this may cause additional problems such as structural alterations that affect the protein's functional characteristics. Furthermore, NaOH must be used to modify the pH throughout the extraction process in aqueous extraction, and some safety concerns may occur based on the amount and concentration of NaOH utilized. Aqueous extraction has been proposed as a less expensive method of preparing concentrates than isolates. Even yet, dry fractionation is still less expensive than aqueous extraction (Ismail *et al*., 2020). Drying the extract is the last stage in protein extraction.

4.0. Functionalization Strategies:

4.1. Chemical Modification:

A popular and beneficial method for improving protein function is chemical modification, which has the noteworthy qualities of high specificity, affordability, and ease of usage. This method introduces new chemicals that alter protein structure and function, making it easier to modify certain protein features. These changes could involve utilizing the reactivity of amino acid side chains or inhibiting particular protein side chains to provide the intended improvements (Feng et al., 2021). Functionalization strategies are given in the table below:

Table 2: Different protein functionalization strategies with their applications

Strategy	Description	Applications	Advantages	Drawbacks	Reference
Extrusion	Use of high temperature and pressure to denature proteins and form new structures	Meat analogs, snacks, textured vegetable proteins	Improved texture, solubility, and digestibility	High energy, loss of heat-sensitive nutrients, equipment costs	Li et al., 2024

High-pressure processing	Use of high pressures to alter protein structure without high temperature	Ready-to-eat meals, juices, meat analogs	Retention of nutritional quality and bioactive compounds	Limited to specific food matrices, not inhibit all microorganisms	Mulla et al., 2022
Ohmic heating	Electrical resistance heating for uniform and rapid heating	Soups, sauces, ready-to-eat meals	Enhanced gelation, emulsification, and nutrient retention	Uneven heating, careful control to avoid over-processing	Avelar et al., 2024
Fortification	Adding essential vitamins and minerals to enhance nutritional value	Fortified beverages, protein bars, snacks	Addressing micronutrient deficiencies	Nutrient interactions that affect bioavailability, alter taste and texture	Khan et al., 2024
Enzymatic treatment	Use of enzymes to modify protein structures	Protein hydrolysates and functional foods	Improved solubility, digestibility, and functionality	Cost of enzymes, undesirable changes in flavor	Ravindran et al., 2024
Scaffolding	Creating 3D structures mimicking meat texture	Meat substitutes and plant-based meats	Improved texture and mouthfeel in meat analogs	Complex and expensive processes, challenges in replicating meat texture and flavor accurately	Jahangirian et al., 2019
Precision fermentation	Use of microbes to produce specific proteins for peptides	Dairy alternatives and protein supplements	Improved nutritional profiles and functional properties	Production cost, scaling up complexity, allergenicity, and regulatory challenges	Farid et al., 2024
Blending with other proteins	Combining plant proteins with other sources	Mixed protein powders and meat analogs	Balanced amino acid composition and improved texture	Incompatibility between protein sources, taste, and texture issues	Keppler et al., 2020

4.1.1. Glycation:

Early, medium, and advanced stages of the Maillard reaction result in complex non-enzymatic conjugates between the protein's free amino group and the reducing sugar's carbonyl group (Benanti et al., 2023). Under controlled conditions, decreasing sugar carbonyl residues during the initial stages of the Maillard phenomenon (referred to as glycation) and intentionally creating covalent bonds between protein ε-amino groups can improve the techno-functionality of proteins (Higa et al., 2023). Glycation-driven alteration has been shown in recent research to increase protein solubility, and emulsion characteristics (Zheng et al., 2022). Proteins and carbs gain surfactant benefits as a result of glycation, creating new compounds with increased value. Covalent binding's steric hindrance effects stop macroaggregates from forming (Kutzli et al., 21). Furthermore, researchers demonstrate that proteins with increasing glycation levels have decreased hydrophobic nature and surface operations, with soluble dissolved in glucose fractions of protein showing greater surface activity than unable-to-dissolve fractions (Feng et al., 2021). For high internal phase emulsions (HIPEs), glycated pea protein is another effective Pickering stabilizer. Remarkably, HIPEs' resistance to oxidation processes and thermal stability are further improved by increasing the degree of glycation. These results demonstrate how glycation-driven changes can improve the characteristics and functionality of proteins for a range of uses (Ertugrul et al., 2021). Protein functioning and characteristics can be greatly enhanced by glycation and related changes, creating intriguing opportunities for their further use.

4.1.2. Conjugation:

The intricate chemical process of protein-phenolic conjugation entails the covalent or non-covalent binding of polyphenolic chemicals to proteins (Parolia et al., 2022). When these phenolic moieties of phytochemicals attach to certain residues of amino acids on the surface of the protein, depending on the circumstances, it may be irreversible or reversible (Liu et al., 2023). Types of polyphenols, proteins, and conjugation conditions all influence the precise effects on protein functionality. The process involves non-covalent interactions, covalent bonding via oxidation, and hydrogen bonding (Pang et al., 2021). The procedure may alter the food system's flavor, color, and nutritional qualities by altering its physicochemical characteristics, solubility, stability, and bioactivity (Parolia et al., 2022). A flexible method, protein-phenolic conjugation can enhance many aspects of protein functioning and help create potential foods with improved bioactive qualities and stability.

4.1.3. Complexation:

Complex coacervation is the method by which oppositely charged polysaccharides voluntarily combine to create a thick layer under their isoelectric point. This phase separation is brought about by electrostatic attraction between the oppositely charged components and is further regulated by surface charge-dependent schematics of phases. The protein and polysaccharides are the factors of the coacervation process that affect how complex coacervation affects protein functionality (Chang et al., 2016; Naderi et al., 2020). By serving as a reservoir, the coacervate phase releases proteins that are encapsulated gradually, providing the release of properties in a controlled way that is useful in nutraceuticals and pharmaceuticals. Furthermore, emulsion-based compounds exhibit superior bacterial and active ingredient retention (Yildiz et al., 2018). Protein functionality can be greatly affected by complex coacervation, which makes it a flexible strategy with potential uses in a range of sectors.

4.1.4. Acetylation:

Proteins can have their net charge changed chemically. By transfer of the acetyl group to the amino acid group on the protein surface, acetylation prevents aggregation. Additionally, by revealing hidden hydrophilic and hydrophobic components, this mechanism promotes subunit dissociation (Shen et al., 2021). Protein functionality is greatly impacted by the chemical modification process known as protein acetylation, which adds acyl groups to particular amino acid residues. Site, acyl group type, and native structure and function of the protein all influence the specific consequences. To achieve the intended functional changes while preserving protein, the acetylation process must be carefully planned and managed (Akharume et al., 2021). Examination of the acetylation of rice protein; found that it improved the water-binding capacity and emulsifying qualities at pH 8. The foaming capacity somewhat declined, while the oil absorption capacity remained mostly unchanged (Miedzianka et al., 2023).

4.2. Physical Modification:

Physical techniques that are non-chemical or enzyme-based offer simple ways to enhance plant proteins' functioning. Chemical methods are not as cost-effective, environmentally friendly, or as widely accepted as physical procedures, which include both thermal and non-thermal techniques (Pan et al., 2022).

4.3. Thermal Modifications:

The activation energy is needed to break a range of protein bonds, including hydrogen, electrostatic, disulfide, and peptide bonds. When proteins change from their original form to a semi-molten globule state, the increased heat mobility disrupts the tertiary structure. Furthermore, the protein's core releases sulfhydryl, hydrophilic, and hydrophobic groups throughout this process (Raikos et al., 2015). Therefore, by using controlled heat, food protein constituents can have their structures altered to improve certain functional qualities. Although its effects on protein solubility may not be significant, heat treatment of several plant proteins has been demonstrated to enhance their gelation, foaming, and water absorption ability (Choudhary et al., 2023).

4.3.1. Microwave Heating:

The energy of microwave radiation can be absorbed by polar protein groups, which can lead to fluctuating pole motion and the production of free radicals. This method successfully breaks disulfide and hydrogen bonds, which eventually causes proteins to unfurl. Consequently, the intensity of hydrophobic group exposure increases, improving surface contacts (Hadidi et al., 2021). Recent research concentrated on how different protein characteristics were affected by microwave treatment. Mu et al. looked at how laccase-induced gel characteristics were impacted by different power levels of microwave pretreatment (0–600 W). Compared to untreated samples, the treated samples showed a gel strength that was more than 2.2 times greater. Furthermore, laccase-induced soy protein gel's storage modulus and water-holding ability were greatly enhanced by microwave heating. Additionally, the secondary structure of the gel samples changed as a result of the microwave treatment (Mu et al., 2020).

4.3.2. Infrared Radiation Heating:

With wavelengths between 0.75 and 1000 µm, infrared (IR) radiation is classified as non-ionizing electromagnetic radiation. It is situated in the space between the microwave and ultraviolet spectrums. Between 430 THz and 300 GHz, these waves create vibrations in materials like water molecules, which heats the medium (Manyatsi et al., 2023). Infrared (IR) radiation can impact proteins by releasing free radicals from atomic bonds within the protein structure. After being exposed to radiation, these liberated free radicals can disrupt a variety of connections between protein molecules, producing hydroxyl radicals, various radical types, and superoxide anion radicals.

4.3.3. Ohmic Heating:

A thermo-electric process that unfolds proteins, reduces particle sizes and improves their functional qualities is activated when an alternating electric current is applied to a protein suspension. When compared to conventional heating techniques The researcher discovered that the protein in soybean milk was affected differently by ohmic heating, boosting free amino groups by 14% while lowering the amount of sulfhydryl and surface hydrophobicity. Functional attributes, decreased foaming activity, while the protein structure stayed mostly unaltered. Remarkably, the indicator of emulsifying activity rose by 38% whereas the index of emulsion stability index dropped by 65% (Miranda et al., 2023). Pereira et al. looked into how ohmic heating affected soybean protein isolate and discovered that there were notable variations in intrinsic fluorescence and a 36% reduction in immunoreactivity at 50 Hz and 95 °C (Pereira et al., 2021).

4.4. Non-Thermal Modifications:

Thermal and non-thermal physical activities offer benefits including fast processing times, cost-effectiveness, and clean labeling when compared to chemical or enzymatic processes (Pan et al., 2022).

4.4.1. High-intensity Ultrasound:

Using ultrasonography causes a variety of phenomena, including shear, cavitation, turbulent flow, and micro-streaming. HIU in the 20–100 kHz frequency range can enhance the solubility, emulsification, and gelation of proteins. Proteins may partially unfold when HIU is applied, resulting in smaller particles. Furthermore, the heat and pressure produced by HIU help to create protein aggregates that have more mobility and flexibility (Zhang et al., 2022). Investigations were conducted into the effects of different HIU amplitudes (25, 50%, and 75%) and durations (5, 10, and 20 minutes) on pea protein isolate. Longer duration and greater sonication amplitude resulted in smaller particle sizes, enhanced surface hydrophobicity, and enhanced solubility of proteins. These physicochemical alterations increased emulsifying activity and emulsion stability values, decreased interfacial tension, and enhanced protein adsorption at the oil-water interface (Mozafarpour et al., 22). Numerous investigations have demonstrated that HIU can enhance the solubility, emulsification, and other desirable features of proteins by causing structural alterations. However, the kind of protein, the state of HIU, and the degree of treatment may all affect the precise consequences.

4.4.2. High Pressure:

For a few minutes, Hydrostatic pressures between 100 and 800 MPa are applied during High pressure (HP) treatment. Plant proteins' solubility and functional qualities may be impacted by this treatment in both favorable and negative ways (Ahmed et al., 2018). Protein hydrophobicity usually increases and solubility decreases due to unfolding and denaturation when exposed to HP. But after being treated with HP certain proteins, such as the protein found in ginkgo seeds, have superior emulsifying and heat-stable properties (Olatunde et al., 2023).

4.4.3. Cold Plasma:

A partially ionized gas made up of a combination of reactive ions, neutral atoms, molecules, and electrons, cold plasma is sometimes referred to as non-thermal plasma or low-temperature plasma. Certain gas molecules ionize and create a plasma state when an electric field is applied to them, creating cold plasma (Basak et al., 2022). It has a variety of reactive species that can react with materials and surfaces, including ions, excited molecules, and free radicals. High-energy cold plasma can cause covalent connections to break and macro clusters to open within protein structures, which reduces particle size (Zhou et al., 2016). To improve the contact and the water molecules' attachment to the protein surface, reactive species produced by plasma encourage the inclusion of particular hydrophilic groups. However, protein micelles may become crowded by prolonged plasma therapy due to an increase in water interactions, which, after a given amount of exposure time, reduces solubility (Zhang et al., 2021).

4.5. Enzymatic Modification:

A popular bioprocess method, enzymatic hydrolysis has many benefits over chemical techniques, including gentler reaction conditions and simpler handling and control throughout the reaction process. Proteins cleave polypeptide bonds in the enzymatic technique, releasing hydrophobic, carboxyl, and active amino groups. As a result, this procedure results in reduced particle sizes and enhances the proteins’ general functioning (Franck et al., 2019). Every study indicates that enzymatic treatments have a positive influence on the functional characteristics of various protein sources. Pea proteolysis was examined by Arteaga et al. Who concentrated on how high molecular weight peptides break down and how that affects allergies (Arteaga et al., 2020). Multiple enzyme treatments (papain, trypsin, bromelain, esperase, savinase, and alcalde) improved the solubility, foaming, and emulsifying qualities of pea protein isolate while also lowering its allergenicity (Arteaga et al., 2021). Likewise, the trypsin-treated rice bran protein showed enhanced flexibility and fluidity as well as better emulsifying and solubility qualities (Wang et al., 2018). While highlighting the significance of comprehending their impact on functional qualities, these studies show the possible use of enzymatic protein hydrolysates across numerous industries (Trigui et al., 2021).

5. **Potential industrial applications of plant-based proteins:**

Globally, and especially in the US and the EU, animal-based proteins including meat, eggs, and milk are the primary sources of protein intake. However, wheat and legumes are eaten as animal feed (Rashwan et al., 2023). Significant dietary adjustments are necessary for a balanced diet since the food and feed system is connected to both planetary and health boundaries (Bian et al., 2023). Research has concentrated on creating plant-based gluten, lactose, and high-protein vegetarian meals as potential foods to boost their economic value, customer acceptability, and health advantages (Hadidi et al., 2023). Different industrial applications of PBPs are given in the table below:

Table 3: Industrial applications of proteins

Source	Extraction method	Protein treatment	Food product	Comments	Reference
			Supplements in food products		
Rice brain protein	Alkali extraction at pH 7-12, temperature 40-80°C, time 15-75 min	-	Biscuit	Improvement in fracture strength of biscuits	Yadav et al., 2011
Sunflower meal	Clarification and precipitation, using 10% NaCl	Purification of protein using chlorogenic acid and emulsification	Bread	Optimum dough acidity, reduced time up to 20-25 min, increased amino acid content	Shchekoldia & Aider, 2014
Quinoa	Alkali extraction at pH 10	Lyophilization and heat denaturation	Cupcakes	Improvement in water activity and firmness	Lopez et al., 2019
Soy protein	-	-	Encapsulation of capsaicin, used in noodles	Capsaicin-enriched noodles, help in the retention of capsaicin	Li et al., 2013
			Hydrogels for delivering nutraceutical components		
Soy protein-based hydrogels	-	Ultrasound pre-treatment of transglutaminase	Delivering riboflavin	Improved riboflavin encapsulation	Hu et al., 2015

		-catalyzed hydrogels			
Soy protein-based hydrogels	-	Soy polysaccharide nano-gels: synthesized by heat treatment high-pressure homogenization at pH 4	Nanogels are suitable for delivery of folic acid in food and beverages	Folic acid remains natural and is released in the intestine at a neutral pH	Ding et al., 2013
Soy protein-based nano-hydrogels	-	Dextran nano-gel (soy protein) using ultrasonication	Delivering riboflavin	65.9% encapsulation efficacy at 250µg/ml riboflavin concentration; Nano gel faster release at simulated intestinal fluid,	Jin et al., 2016
Soy protein isolate	Gelation of aqueous soy protein from geni pin cross-linking agent	-	-	SPI gel, site-specific drug delivery in the intestine	Norouzi et al., 2019
		Proteins as stabilizers in food products			
Lupin	Spray drying and alkali extraction at pH 8	-	Food-grade Pickering stabilizers	Improvement in creaming and coalescence stability	Burgos-Diaz et al., 2019
Peanut protein	Alkali extraction and acid precipitation	-	Food-grade Pickering stabilizers	-	Ning et al., 2020
Lentil, pea, faba bean protein	-	-	Natural emulsifiers in oil-in-water emulsions that are fortified with omega-3 fatty acids	Emulsifiers for stabilizing and foaming algae 10% in oil-in-water emulsions produced during high-pressure	Gumus et al., 2017

				homogenization	
Pumpkin seed protein	Alkali extraction with isoelectric precipitation	-	Food emulsifier	Most stable emulsions at pH 8	Bucko et al., 2015

5.1. Nondairy alternative products:

The significance of non-dairy milk products, such as almond milk, mung bean milk, soybean milk, and nondairy yogurts, has been brought to light by worries about animal proteins, lactose intolerance, high cholesterol, milk allergies, anemia, and coronary heart disease (Wang et al., 2023). These products are highly nutritious due to their non-allergic proteins, dietary fiber, essential fatty acids, minerals, vitamins, and bioactive compounds (Olabiran et al., 2023). Quinoa yogurt's rheological properties, texture, and storage stability have been enhanced by fermentation using *Weissella confusa* and a modified commercial starter. The fermented quinoa yogurt is also more bioavailable and digestive thanks to the modified starter (LIU et al., 2023). An alternate method for making lactose-free cheese is to utilize plastic-based milk (PBP). Soy protein concentrate-enriched soft cheese-like products have demonstrated improved production, sensory evaluation, and protein and fat levels (Rinaldoni et al., 2014). The research examined the possibilities of making a cheese-like product by partially substituting almond milk for soy milk. The findings demonstrated a considerable increase in both protein content and total titratable acidity (Arise et al., 2020). It has been shown that zein and PPI-based plant-based model cheeses can mimic the melting of real cheese (Sutter et al., 2023). PBPs have demonstrated promise as a dairy substitute for drinks, yogurt, and cheese production due to their higher nutritious content and more palatable taste to consumers (Minic et al., 2024).

5.2. 3D food printing and meat analogs:

Using a range of digital model files and raw materials, 3D printing is a cutting-edge manufacturing technique that shapes food goods (Qui et al., 2023). Small-scale food manufacturing, tailored nutrition for different consumer groups, and individualized food design are all possible applications for this technology (Carranza et al., 2023). Good 3D food printing properties may be found in a food matrix that has a combination of SPI, sodium alginate, and gelatin; SPI and gelatin together provide exceptional geometries. Raising the temperature to 25°C caused the rheological index to rise quickly, preserving the desired form and sustaining the deposited layers (Chen et al., 2019). To make a high-protein edible ink for 3D-printed meat analogs, SPI, wheat gluten, and rice protein powders were combined. The viscoelastic characteristics and pseudoplastic behavior of the protein-enriched inks were enhanced by decreasing storage modulus and apparent viscosity as the quantity of rice protein increased (Qui et al., 2023). Combinations of PPI and SPI with alginate modified by RGD were assessed as possible bio-inks for cellular printing. Mold-based proteins showed enhanced stiffness and stability, enabling unhindered BSC maturation and proliferation, they showed (Lanovici et al., 2022). Using SPI, fish analogs were produced, and hybrid meat analogs derived from pea and chicken proteins were examined (Shi et al., 2023). A moisture content of over 70% was found in both hybrid and PPI-only cooked meat analogs, which is similar to chicken mince (Wang et al., 2023).

5.3. Nutrient supplements and food additives:

Proteins provide food with more nutrients and make it nutrient-dense, making them vital dietary supplements in the human diet. They have many practical uses, including maintaining bone health, promoting muscle growth with aging, controlling weight, and providing nutrients (Kritikos et al., 2021). Proteins are bioactive substances that function as the building blocks of the immune system and are essential for maintaining cardiovascular health and preventing disease. Plant proteins help athletes achieve their protein demands, decrease cholesterol, preserve bone health, and build muscle in older persons. Studies have looked into the usage of dry fruits, nuts, legumes, cereals, and pseudocereals as protein supplements (Sengupta et al., 2016). In one study, low amounts of caffeic acid and chlorogenic acid in functional wheat bread were made using sunflower meal protein isolate (SMPI), which increased the bread's bulk volume and nutritional value (Shchekoldina et al., 2014). Another study created lacto-vegetarian-friendly eggless cakes using xanthan gum (XN), isolated pea protein (PPI), and emulsifier mixtures. Regarding specific gravity, crumb color, and crumb pore characteristics, the recipe for an eggless cake with PPI, XN, and SL was demonstrated to be equivalent to the usual control cakes (Lin et al., 2017).

5.4. Synthesis of nanoparticles:

Many encapsulation systems, such as complex coacervates, nano-gels, nanofibrils, Pickering emulsions, and nanocrystal composites, have been made using protein-based polymers (PBPs). Amphiphilic characteristics, abundance, biodegradability, biocompatibility, and balanced amino acid profiles are some of these nanoparticles' special qualities. Complex coacervates, nano-gels, nanofibrils, Pickering emulsions, and nanocrystal composites are examples of nano-carriers that have been created and enhanced using soy, wheat, pea, corn, and sorghum proteins, among others (Pu et al., 2020). To stabilize β-carotene, wheat gluten nanoparticles (WGN), and wheat gluten nanoparticle-xanthan gum (WGN-XG) complexes have all been encapsulated using Pickering emulsions. These emulsions stopped chemical degradation during storage and were resistant to aggregation. They have better β-carotene bio-accessibility and can be thermally sterilized (Fu et al., 2019). For the delivery of curcumin, special complex nanoparticles have been made using soy protein isolate (SPI) and cellulose nanocrystals (CNC) serve as polymer matrices. These nanoparticles are tiny, have high encapsulation efficiency, and have a low polydispersity index (Wang et al., 2020). Additionally, composite nanoparticles of core-shell pea protein with carboxymethylated corn fiber gum have demonstrated outstanding curcumin encapsulation performance, exhibiting strong chemical and thermal stability, good water dispersibility, and high curcumin loading efficiency (Wei et al., 2020). Due to the various applications of PBPs, many countries are investing in their research and marketing as shown in Figure 4:

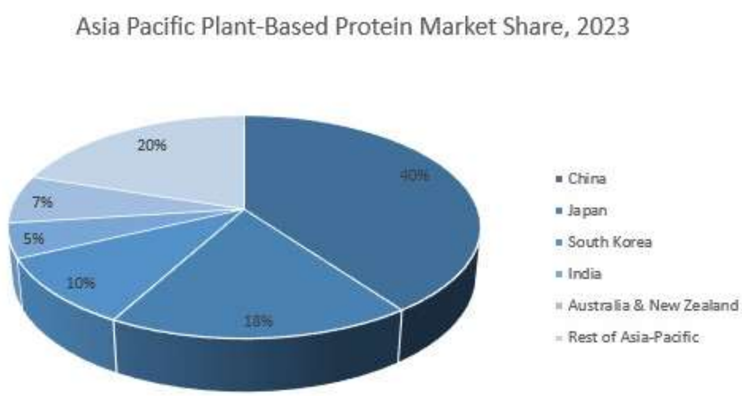

Figure 4: Asia Pacific plant-based protein market share, 2023 (Virtue market research, 2024)

5.5. Bioplastics and packaging films:

Cottonseed protein, sorghum protein, wheat gluten, soy protein, and maize protein are examples of plant waste proteins (PBPs), which have become a new class of environmentally benign and green products (Patnode et al., 2021). Because of their low cost, simplicity of manufacturing, versatility, and wealth of natural resources, petroleum-based polymers may eventually be replaced by these second-generation bioplastics. They are employed in several environmentally delicate industries, including the biomedical field, packaging, and agriculture (Jimenez et al., 2019). Scientists have successfully created films using zein and modified soy proteins, which show encouraging mechanical and physical properties. Micro-fibrillated cellulose and natural additives like sorbitol and glycerol enhanced the surface hydrophobicity and flexibility of the film (Patnode et al., 2021). In contrast to aqueous ethanol-cast films and other zein films, films created from high-quality protein maize zein were less translucent, absorbed less liquid, and swelled less (Baloyi et al., 2023). A study on film-forming solution (FFS) based on soy protein isolate (SPI) found that adding 1 mmol/L cysteine decreased the perceived viscosity of FFS, but this effect was negligible. Water vapor permeability and contact angle rose with increasing cysteine concentration, whereas film elongation at break decreased (Jiang et al., 2023).

6. Potential health effects of PBPs and its products:

Plant proteins are becoming more and more popular because of their potential for health benefits and bioactivity. Phytochemicals with anti-inflammatory, antioxidant, and anti-carcinogenic qualities, including polyphenols, flavonoids, and antioxidants, are abundant in these proteins. Additionally, they contain or have the potential to create bioactive peptides that may be used to inhibit enzymes, modify immunological responses, and control blood pressure. These qualities not only improve well-being and health but also make it easier to create nutraceuticals and functional meals with targeted health advantages. The continuous investigation into the bioactive properties of plant proteins points to a bright future for food innovation in preventive healthcare and nutrition (Fawzi et al., 2022).

6.1. Antioxidant and Anti-inflammatory properties:

The creation of reactive species and antioxidant defense are out of balance, leading to oxidative stress, which is a primary cause of many diseases. For the body's antioxidant system to be strengthened, dietary components such as proteins, peptides, amino acids, and phenolics are essential (Chauhan et al., 2015). Flavonoids, phenolics, and tannins found in plants like pulses strengthen antioxidant defense (Olabiran et al., 2023). Polar amino acids lower and bind metal ions, whereas hydrophobic amino acids degrade and scavenge free radicals. By serving as hydrogen donors during peroxidation, hydrophobic residues strengthen antioxidant defenses. Glycinin, millet protein hydrolysates, phaseolin peptides, and pseudo-cereal proteins from quinoa and amaranth seeds are all crucial for reducing the effects of oxidative stress (Chauhan et al., 2015).

Anti-inflammatory, anti-thrombotic, and anti-hypertensive actions are among the bioactive qualities of plant proteins. Lentils, lupin, chickpeas, peas, and common beans all create protein hydrolysates that have anti-hypertensive properties. The anti-inflammatory properties of millet protein hydrolysates, lupin peptides, rice globulin peptides, and wheat peptides are possible (Sandoval et al., 2021). 7S protein subunit β-conglycinin can improve lipid profiles, lower obesity-related problems, and have anti-inflammatory qualities. Rats given β-conglycinin orally every day can have lower triglycerides, LDL cholesterol, and total cholesterol (Kim et al., 2021)

6.2. Anti-diabetic and anti-obesity properties:

Diabetes risk is significantly decreased by vegetarian diets; however, it is unknown how this reduction is affected when plant protein is substituted for animal protein. You can reduce your risk of type 2 diabetes by 23% by substituting 5% of your caloric intake with vegetable protein, according to studies (Malik et al., 2016). A 2015 meta-analysis of randomized control trials found that diabetics' HbA1c, fasting glucose, and fasting insulin levels significantly improved. Both diets decreased blood lipid markers, body weight, BMI, and HbA1c comparably during the intervention, according to a prospective clinical trial; however, there was no difference between the plant protein diet and the animal protein group (Viguiliouk et al., 2015).

Consuming protein is essential for strength and endurance training, and active people frequently fulfill the requirements for leucine content and meal total protein of 2-4 g and 20-40 g, respectively (Nowson et al., 2015). The majority of research on the synthesis of muscle proteins, particularly after resistance exercise, concentrates on superior animal proteins, like those found in dairy or eggs (Jager et al., 2017). Studies using different plant proteins, however, have demonstrated that consuming more protein can raise 24-hour muscle protein synthesis (MPS) associated with rest and activity over the baseline level. Lean body mass and strength improvements brought on by resistance exercise and short-term MPS can be effectively facilitated by whey protein; however, higher dosages of plant proteins can yield comparable fitness results (Saracino et al., 2020).

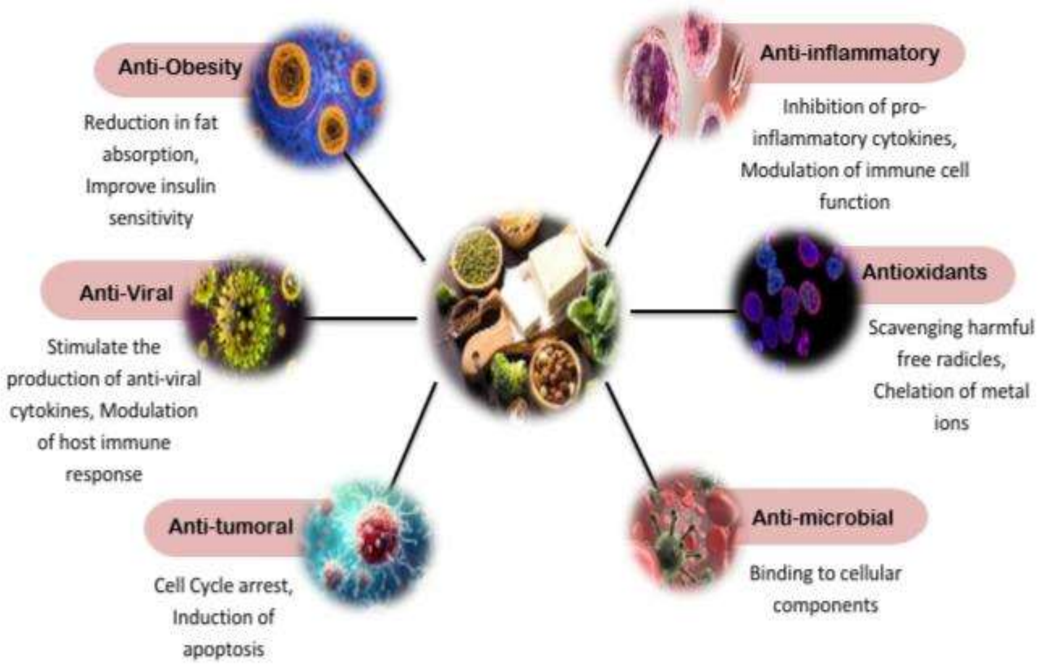

Figure 5: Potential health benefits of PBPs

6.3. Cardiovascular diseases and metabolic risk factors:

Cardio-metabolic risk factors include low-density lipoprotein cholesterol and apolipoprotein B which have been demonstrated to be decreased by plant proteins. In support of plant protein consumption, lower indications of cardiovascular disease were found in a 2017 systematic review and meta-analysis of 112 clinical investigations. Plant proteins have been shown in a recent meta-analysis to reduce lipid profiles in individuals with hypercholesterolemia (Li et al., 2017). Healthy Lifestyle in Europe by Nutrition in Adolescence (HELENA) research study claims, adolescents' diets should contain more plant protein to help reduce obesity and enhance cardio-metabolic parameters (Lin et al., 2015). Nonetheless, several scientists advise against generalizations regarding plant protein's superiority over animal protein due to insufficient and contradictory research.

6.4. Anti-microbial properties:

Plant proteins have been found to have antibacterial defense mechanisms that naturally prevent the development of a variety of infections. Chop proteins and peptides, lupin protein hydrolysates, and chickpea-methylated proteins have all demonstrated antibacterial efficacy against a range of foodborne pathogens (Osman et al., 2016). Cowpea and lupine proteins have demonstrated antibacterial effectiveness against a wide range of bacteria, hence reducing the growth of microorganisms in meat products (Osman et al., 2021). These proteins, like soybean proteins and peptides and various extracts from medicinal plants, cause bacterial cell deformation and lysis (Bessada et al., 2019). Buckwheat, quinoa, and amaranth are examples of pseudo-cereals that have demonstrated antibacterial properties. Protein isolates from amaranth and quinoa had a notable inhibitory effect on Escherichia coli and Staphylococcus aureus. These plant proteins show potential for new medical and agricultural uses and provide sustainable substitutes for conventional antimicrobials (Mudgil et al., 2019).

6.5. Anti-cancer properties:

Because of their genotoxicity-free status, genotype specificity, and adjuvant potential, legumes have been recognized as promising cancer treatments (Bessada et al., 2019). Legumes contain a bioactive peptide called β-conglycinin, which can stop the growth of cancer cells by causing apoptosis and interfering with the signaling pathways of cancer cells. While glycinin's hydrophobic peptides have strong anti-cancer properties, pulse proteins from legumes have demonstrated anti-gastrointestinal cancer potential (Fu et al., 2022). The Arg–Gly–Asp tripeptide soy lunasin functions as an anticarcinogen. The eating of whole cereals is associated with a decreased risk of chronic degenerative illnesses. 20 Research on plant proteins that have antitumoral properties gives up a possible path for the development of new natural chemicals for cancer therapy (Carbonaro et al., 2022).

6.6. Plant protein intake and its relationship to mortality:

According to a study from the NIH-AARP Diet and Health study, consumption of plant protein was significantly inversely connected with both cause-specific mortality from cardiovascular disease and stroke as well as all-cause mortality in both males and females. A 10% decrease in overall mortality was linked to substituting just 3% of the protein diet with plant protein for both men and women (Huang et al., 2020). This supports a previous systematic review and meta-analysis on the link between mortality risk and protein intake (Naghshi et al., 2020). An increased consumption of total protein was linked to a lower risk of death from all causes. These studies indicate that mortality and lifespan may be improved by increasing the amount of plant protein consumed instead of animal protein.

7. Future technological challenges for processing alternative protein products:

The sensory characteristics of AP products are not well accepted by consumers due to their lack of certain parameters. These technological problems stem from molecular and physicochemical disparities in the techno-functional characteristics of plant and animal proteins (McClements et al., 2021). Plant proteins are globular and stored as preserved nutrients, making protein extraction necessary. However, they can undergo heat gelation and possess emulsifying properties, but require a concentration above that of animal proteins (Sim et al., 2021). Chickpea and protein from soybeans have similar solubility and emulsifying characteristics that require higher egg proteins, but temperature and more achieve the chance to be comparable in texture (McClements et al., 2021). Insect proteins exhibit low foaming characteristics and are known to undergo heat-induced gelation. They are divided into complete bug powder and, solvent-extracted proteins obtained from bugs with their techno-functional characteristics depending on non-proteinaceous materials (Kim et al., 2020). The most difficult component of these proteins is producing models of whole-muscle steak. Industrial substitutes for meat are frequently made using elevated temperatures the extrusion which can be divided into dehydrated (10–40%) and damp (60–70%) extrusion procedures. Damp extrusion creates crystallographic structures that mimic the contractile properties of whole-muscle protein, whereas dehydrated extrusion is frequently used to create texturized vegetarian proteins (Bakhsh et al., 2022). Alternatives of meat are frequently thought to have an elastic feel, little integration, and no moisture. To make up for the low techno-functional qualities of plant and insect proteins, processing aids such as flavoring, coloring, and structure-forming chemicals are employed (Hadi et al., 2021). Other emerging technologies for the production of whole-muscle structures include wet spinning, electrospinning, shear cell technology, and three-dimensional (3D) printing. Although flex cell innovation has demonstrated promise for operations scaling up, more research is required. Depending on the species of microbes, production method, and non-protein molecules employed, microbe-derived proteins exhibit a variety of techno-functional characteristics. Microbial matter produced in biological reactors or other monitored settings is the source of microbe-derived proteins (Schmid et al., 2022). Because of its large insoluble fiber content, dry plant matter has poorer oil binding and foaming qualities than proteins generated from extracted microbes (Ribeiro et al., 2023). Proteins may become destroyed as a result of heat treatment, changing their techno-functional characteristics (Gamarra et al., 2022). Given that the fiber-oriented structure produced by bulk separation visually resembles pulverized meat, creating meat analogs from filamentous fungi seems to be less difficult than creating proteins derived from plants and insects (Dekkers et al., 2018). The environment is still greatly impacted by current technology, even if certain commercial products have been on the market for several years (Santo et al., 2020).

7.1. Nutritional Profile:

Because of the substantial amount of cholesterol and saturated fat levels and low fiber content, vegetarian and vegan diets have been associated with health promotion since they are thought to reduce the risk of long-lasting illnesses (Vatanparast et al., 2020). The health impacts of vegetarian and vegan diets are still being investigated, though, as many of them are categorized as "ultra-processed foods." Customers are unwilling to believe that these goods are honestly nourishing and wholesome (Monteiro et al., 2019). According to new studies that examined the nutritional profiles of commonly accessible plant-based products, they are higher in intake of fiber, lower in energy content, and lower in fat content than animal-based products. However, compared to traditional items, these frequently have higher salt content (Boukid et al., 2022). The dietary protein intake of most products made from plants is lower than that of meat substitutes generated from insects and microbes (Smetana et al., 2021). To give the impression that they are animal-derived, these items are frequently made with proteins extracted from animals and other components. To address the connection between ultra-processed foods and negative health impacts associated with diet, further causation research is required (Bohrer et al., 2019). Metabolome-like polyphenols, also which may be subject to substantial protein extraction and food processing, are the source of the health-positive aspects associated with plant-eating (Monteiro et al., 2019). Only soy protein, brown rice, beans, wheat, and tubers satisfied the FAO/WHO standards for essential amino acids, according to a prior study. Wheat, cannabis, cereal grains, and legumes were among the other plant protein sources that fell short of the necessary amount (Dimina et al., 2022). Combining various plant protein sources may be able to assist get over these problems. It is not advised for children under one-year-old to consume plant-based beverages or formulas as their primary liquid diet (Brusati et al., 2023).

8. Health Concerns associated with plant proteins:

8.1. Anti-nutrients:

One health concern caused by eating a greater amount of protein from plants is the presence of harmful substances in plant foods. Antinutrients are substances that are naturally produced by plants and can have a variety of detrimental effects, including affecting the usage, incorporation, or metabolism of nutrients in meals. The adverse effects of harmful substances include bowel disarray, swelling, autoimmune illnesses effects (e.g., lecithin and some saponins), protein maldigestion (trypsin and protease enzyme inhibitors), carbs maldigestion (the amino acid alpha inhibitors), mineral malabsorption (phytates, tannins, and oxalates), disruption of thyroid iodine uptake (goitrogens), psychological consequences (conversion of grains these compounds to exorphins), and anemia and autoimmune illnesses effects. Antinutrient side effects have frequently been seen in animals given unprocessed plant proteins, and these findings have made consumers wary of consuming certain plant-based meals. Antinutrients do not, however, necessarily have negative effects on the body; in certain situations, they may have beneficial consequences (Popova & Mihaylova, 2019). Phytates, lectins, phenolic compounds, enzyme inhibitors, and saponins are some of the ingredients that may help reduce low levels of blood glucose, plasma cholesterol, and triglycerides. Some saponins, phytates, protease inhibitors, lignans, and phytoestrogens may lower the risk of cancer, while others may aid in liver function and decrease platelet agglutination (Yang, 2022). Tannins may also have antibacterial properties. Consequently, the low concentrations of these "antinutrients" may be responsible for some of the health advantages of plant-based meal plans. Lastly, further techniques that can drastically reduce the number of antinutrients in plant proteins include sopping, the process of fermenting growth, warming, radiation exposure, and chromosomal advances in technology. It is possible to significantly increase the bioavailability of canola proteins by removing contaminants such as insoluble fiber, erucic acid, phytates, and lactic acid by food processing processes. Compared to when the protein is still in the whole food matrix, plant protein isolates and isolates are much easier to digest since they are often treated to eliminate the majority of the nutrient antagonists. For instance, soy flour has a protein digestibility of just 84%, whereas soy protein isolate has a protein digestibility of 96% or more (Hughes et al., 2011). Antinutritional factors in PBPs are given below:

Table 4: Antinutritional factors in plant-based proteins

Protein source	Phytates	Tannins	Oxalates	Lectins	Protease inhibitors	References
Lentils	X[2]	X	X[1]	X[2]	X[2]	Samtiya et al., 2020
Chickpeas	X[2]	X	X	X[1]	X[1]	Soni et al., 2022
Black beans	X[2]	X[1]	X	X[2]	X[2]	Meka, 2021
Quinoa	X	X	X	X[1]	X	Samtiya et al., 2020

Edamame	X^1	X	X	X	X^2	Manzoor et al., 2021
Tofu	X	X	X	X	X	Riley, 2022
Tempeh	X	X	X	X	X	Bester, 2023
Hemp seeds	X	X	X^1	X	X^1	Bester, 2023
Chia seeds	X	X	X	X	X	Samman et al., 2023

X mentioned as Low; X^1 as Moderate; X^2 as High

8.2. Soy Protein and Isoflavones:

They contain isoflavones, which are chemicals that resemble estrogen, the focus of wellness statements and potential adverse health effects has been the protein found in soybeans. Because of research using massive dosages queries have been raised regarding the potential hormonal imbalance of reproductive hormones caused by isoflavones found in soybeans in rats or lab cultivation of cells (Messina, 2016). Over the past 15 years, however, several study lines have demonstrated that worries about negative hormonal consequences from physiological intakes of soy products are mostly unwarranted. The European Food Safety Authority conducted a comprehensive assessment of the effectiveness of interferon supplements for older and pregnant women in 2015. The findings indicated that daily doses of 35–150 mg of isoflavones in this group of individuals did not change thyroid hormone status, uterus thickness, or histological adjustments in the uterus during 30 months, nor were they linked to the risk of carcinoma of the breast (European Food Safety Authority, 2015). There has been no apparent shift in free testosterone, the binding globulin for sex hormone-independent masculine hormones, or free androgen index by consuming up to 60 g of soy protein per day, according to a meta-analysis of 15 placebo-controlled studies involving men of different ages (Hamilton-Reeves et al., 2010). Potential worries about how soy meals affect thyroid function could prevent people from consuming more soy protein (Kim et al., 2021). Soy and isoflavones have no overall influence on thyroid function recent research supports the safety of soy even more. However, the scientists did see a slight elevation in TSH in certain studies, which may not have clinical significance. The absorption of levothyroxine in hypothyroid people using thyroid replacement therapy may be somewhat hampered by soy meals, according to very little case study data. In this case, if the levothyroxine dosage is either raised or scheduled such that it does not overlap with the soy intake, a moderate amount of soy meals may still be justified (Liu et al., 2023). PBPs also cause allergic reactions as given in the figure below:

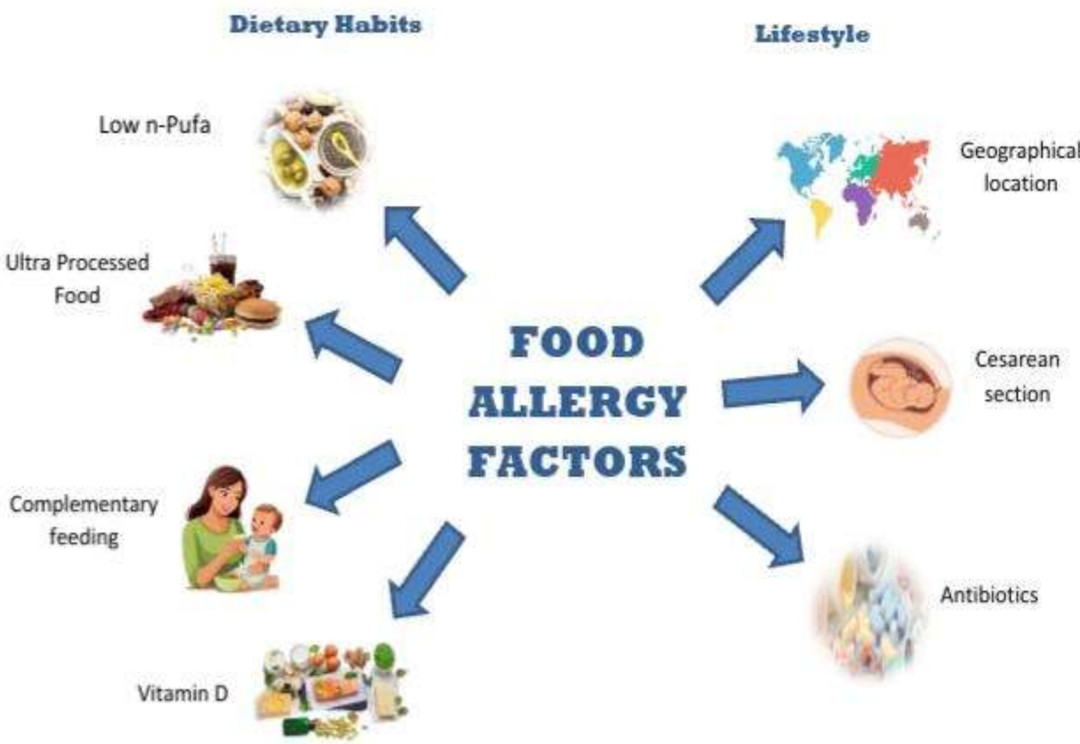

Figure 6: Allergy-causing factors related to PBPs

8.3. Flavor and taste:

Lingering off odors of PBPs may be detected, but using plant proteins—such as those found in legumes—in food is difficult. "Green," "beany," “paint," and "grassy" are common terms used to characterize the off flavors found in soy proteins. Usually ascribed to the origins of the raw material, processing, and/or storage, these off-notes are caused by the peroxidation of unsaturated fatty acids, which is begun by lipoxygenase (Ismail et al., 2020). Raw, preserved, and cooked peas have all been studied for their taste components. Alcohols and their ester derivatives, methoxypyrazines, aldehydes, ketones, and saturated and unsaturated alcohols were among the flavor chemicals that were described (Malcolmson et al., 2014). The volatile taste compounds of peas underwent considerable modifications during storage. In the meanwhile, differences in volatile chemicals across genotypes and between cultivars produced in different crop years. We are not aware of any research on flavor compounds that are retained in novel plant protein components, such as pea protein isolates. Designing protein extraction and processing techniques that produce neutral (bland) products is necessary. Off-aromas have not been successfully masked. Contrasting to taste, which usually deals with a single receptor, the scent is the total pattern of responses from multiple receptor types, making it more difficult to disguise off-tastes like bitter. Instead of trying to cover up the undesirable off-flavors, accurate flavor profiling will reveal strategies to get rid of them (Azarnia et al., 2011).

Conclusion and Future Directions:

Products synthesized by plant-based proteins and plant-based whole foods are trending in the market. PBPs are associated with health benefits, pharmaceutical, and industrial applications. PBPs excel in 3D food printing, meat analogs, non-dairy alternatives, and the benefits of antioxidant and antimicrobial agents increasing their acceptance and development. Their demand continues as consumers increase their knowledge about the sustainability of food supply and the nutritional value of plant proteins. The demand for PBPs may also be fueled by recommendations for current public health proteins. On the other hand, those who prefer plant proteins must know the difference in nutritional value between plant-based proteins and animal proteins when choosing the appropriate diet, especially the vulnerable population should be taken care. Plant protein technology is the major concern area for biotechnology for addressing the safety issues related to PBPs. Monitoring of meat and dairy substitutes (i.e., PBPs) is pertinent to common food safety risks related to PBPs products (e.g., mycotoxins or plant-based contaminants may be present in plant products) or processing. The presence of processing contaminants and anti-nutritional compounds in PBPs were seen as potential hazards, although the knowledge is limited. Innovative techniques like enzymatic treatment and physical processing can intensify their functional properties by modifying protein structures. Extraction of proteins from plant sources is a challenging process including laborious methods associated with aqueous extraction and changes in structure that occur during processing like drying. Proteins' quality and quantity vary depending upon a variety of plants and hence various strategies need to be examined that can help to enhance the yield and quality of proteins. Scientists and the food industry working on indigenous plants like Bambara groundnut (cultivated in West Africa) to explore its potential uses. The use of PBPs in food items has drawbacks as well, such as their lower nutritional content compared to animal proteins and their disagreeable taste and flavor. Allergenicity is another issue that has to be addressed before PBPs replace animal proteins. To safely and effectively include PBPs in diets and expand their applications in the food sector, more work needs to be done to assess their sustainability.

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