

PLANT PROTEINS FOR FOOD APPLICATIONS

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Abstract. *This review aimed to focus on a critical literature overview of diverse plant proteins used in a food application, as well as their technofunctional properties and new product development. The involved methods included literature overview in the last 10 years by using different scientific bases (PUBMED, SCOPUS).*

Plant proteins have gained significant attention as sustainable and health-promoting alternatives to animal proteins in food applications. Derived from diverse sources such as legumes, cereals, nuts, and seeds, plant proteins offer multifunctional properties including emulsification, gelation, and water-holding capacity, which are critical for food formulation. Their incorporation supports the growing consumer demand for plant-based, clean-label, and nutritious products aligned with environmental sustainability goals. However, challenges persist including incomplete amino acid profiles, lower digestibility, and sensory issues like beany flavors, which may affect consumer acceptance and nutritional quality. Advances in extraction, modification, and blending techniques have improved the functional performance and nutritional completeness of plant proteins, enabling their wider application in meat analogs, dairy alternatives, baked goods, and snacks. Future innovations are expected to focus on diversification of protein sources, enhancing product texture and flavor, and leveraging novel technologies such as precision fermentation and AI-driven formulation. Overall, plant proteins represent a versatile and essential component for the development of sustainable, healthy, and appealing food products, contributing to global food security and reduced environmental impact. Continued interdisciplinary research and industry collaboration will be pivotal to overcoming current limitations and maximizing the potential of plant proteins in the evolving food landscape.

Key words: *plant proteins, food, novel food, circular bioeconomy*

Introduction

Plant proteins have emerged as a vital component in food applications due to increasing consumer demand for healthy, sustainable, and ethical dietary alternatives to animal proteins [1]. These proteins, derived from diverse sources such as soy, peas, chickpeas, lentils, faba beans, rice, quinoa, and various nuts and oilseeds (Figure 1), offer substantial nutritional benefits and functional versatility in food product development as summarized in Table 1 [2].

Functionally, plant proteins serve multiple roles in food systems including gelling, emulsifying, foaming, water, and oil holding capacities [3]. These properties are influenced by protein source, amino acid composition, molecular structure, and processing methods such as extraction and drying. For example, globulins and albumins in plant proteins contribute differently to these functionalities, with the legumin-to-vicilin ratio impacting emulsification and gelation [4]. Commercial processing may reduce protein solubility and therefore impact functional performance due to denaturation and aggregation, underscoring the importance of optimized extraction and preparation techniques [5].

Nutritionally, while plant proteins are generally valued as being non-allergenic and easily digestible [6], they may have incomplete essential amino acid profiles compared to animal proteins [7]. Strategies like protein fortification and complementation are used to address these limitations [4]. Additionally, plant proteins have been recognized for their potential to produce bioactive peptides, contributing to health benefits [8].

Despite their promise, challenges include sensory issues such as beany or bitter flavors, variable functionality across batches, and limited commercial availability of some sources [4]. Research emphasizes the need for a comprehensive understanding of the relationship between protein structure, functionality, and processing to better exploit plant proteins in food applications [7]. Innovations in large-scale isolation, modification, and analytical testing are advancing the field.

Overall, plant proteins offer a multifaceted solution for sustainable food production, aligning nutrition, functionality, and ecological considerations [5]. Continued interdisciplinary research and industrial innovation are essential to overcoming existing barriers and expanding their food application potential, thus supporting the shift toward plant-based diets globally [7].

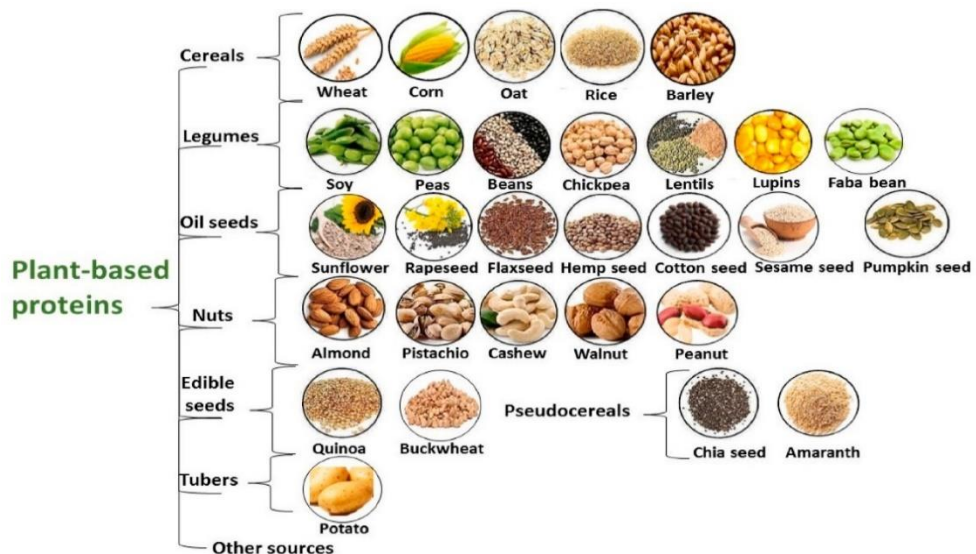


Figure 1. Natural sources of plant-based proteins [2]

The most widely used plant proteins in food products to date are primarily soy, pea, and wheat proteins [9]. These three sources form the foundation of many innovative plant-based foods, including meat and dairy alternatives because of their functional, nutritional, and sensory qualities.

Soy protein is the most established and versatile, widely used in products such as tofu, tempeh, plant-based meat, and dairy alternatives [1,9]. Its high protein content, balanced amino acid profile, ability to form gels and emulsions, and neutral flavor make it a staple in plant-based product formulation [1,9].

Pea protein has recently surged in popularity and is now considered the top plant protein in many new vegan and plant-based food launches [1,9]. Pea's neutral taste, good solubility, hypoallergenic nature, and gelling properties make it ideal for applications in plant-based burgers, drinks, protein bars, and dairy substitutes [1,9].

Wheat protein particularly in the form of seitan (vital wheat gluten), is also commonly used to develop meat analogues due to its unique elastic, chewy texture [10, 11, 12]. Its ease of forming "meaty" structures adds to its appeal, though it is unsuitable for gluten-free products [10,11].

Beyond these three, innovation is expanding to other legumes and seeds. Proteins from faba beans, lentils, chickpeas, sunflower, rapeseed, and oats are being incorporated as product developers seek diversification [9]. Faba bean protein, for example, is gaining ground for its versatility and allergy-friendly profile, while lentil and chickpea proteins are used in both meat and dairy alternatives as well as snacks and bakery products.

Oilseeds such as pumpkin, flax, and chia are increasingly recognized for their protein content and additional health benefits, although their use is often in blends rather than as a sole protein base [13, 14].

Emerging categories also include proteins from quinoa, rice, amaranth, and even algae and mycoprotein (fungal protein such as Quorn). These are valued for their specialty nutrition or sustainability benefits but are not yet as widely used as soy, pea, or wheat.

The classification of plant proteins as novel foods requires that they undergo rigorous safety assessments and regulatory approvals before they can be introduced into the market [1, 9]. This regulatory framework, including the European Union's Novel Food Regulation, ensures that these proteins meet strict safety standards, demonstrate adequate nutritional value, and are properly labeled for consumer transparency [1,9].

Moreover, the development of novel plant proteins addresses important functional aspects such as improving digestibility, enhancing techno-functional properties, and ensuring consumer acceptance [1,9]. These proteins offer not only environmental benefits by reducing reliance on traditional animal-based proteins but also open new possibilities for product innovation in the food sector.

A recent example of this innovation is the approval of protein derived from water lentils (duckweed), known as Rubisco, as a novel food in the European Union, reflecting the dynamic landscape of alternative protein sources emerging in the market [15, 16].

Overall, plant proteins as novel foods represent a promising and growing category of sustainable protein ingredients that are reshaping the future of food through innovation, rigorous safety evaluation, and responsiveness to consumer demands for healthier and more environmentally friendly alternatives.

Table 1. Overview of plant proteins including their characteristics and applications

Plant Protein Source	Common Applications	Key Characteristics	Nutritional Quality	Functional Properties	Notes and Recent Trends
Soy Protein [9,11]	Meat alternatives, dairy substitutes, protein supplements	High protein content; widely studied	PDCAAS ~1.0 (complete protein)	Good emulsification, gelation, solubility	Strong and reliable supply chain; market leader historically
Pea Protein [9]	Meat alternatives, bakery, beverages	High protein, non-allergen, non-GMO	PDCAAS \geq 0.75	Moderate solubility, good emulsification	Growing popularity due to sustainability and functionality
Wheat Protein (Gluten) [11]	Bakery products, meat alternatives	Rich in gluten proteins for texture	Lower in lysine	Good viscoelasticity and binding	Widely used but allergen for some consumers
Rice Protein [11]	Protein supplements, hypoallergenic products	Hypoallergenic, moderate protein content	PDCAAS ~0.6	Good solubility, limited gelling	Used in hypoallergenic and gluten-free products
Faba Bean Protein [9]	Meat alternatives, beverages	High protein, good amino acid profile	PDCAAS \geq 0.75	Good gelation and emulsification	Emerging candidate with good functionality
Quinoa Protein [9]	Protein supplements, health foods	Complete protein with balanced amino acids	High quality (PDCAAS similar to soy)	Good digestibility and emulsification	Considered a "superfood" with added nutritional appeal
Lentil Protein [9]	Meat alternatives,	Moderate protein, good	Moderate PDCAAS	Moderate solubility	Used in blends to improve

Plant Protein Source	Common Applications	Key Characteristics	Nutritional Quality	Functional Properties	Notes and Recent Trends
	protein blends	lysine content			nutritional value
Chickpea Protein [9]	Meat alternatives, bakery products	Good protein content and functional properties	Moderate to high PDCAAS	Good emulsification and foaming	Increasing use in novel plant protein products
Potato Protein [17]	Functional ingredient in food formulations	High lysine content, good nutritional profile	PDCAAS \geq 0.75	Good solubility and gelation	Less common but promising for functional food ingredients

Cereal proteins

Cereal proteins play an important role in food applications due to their widespread availability, nutritional value, and functional properties [11, 12]. Extracted from grains such as wheat, rice, maize, oats, and barley, cereal proteins provide essential amino acids and bioactive peptides with health-promoting effects [11, 12], they contribute to texture, structure, foaming, emulsification, and gelation in various food products. Wheat proteins, notably gluten, form elastic and cohesive networks that are widely exploited in bakery products and meat analogs [12], as presented in Figure 2.

However, cereal proteins generally have lower solubility and limited technological quality compared to animal proteins, which can restrict their versatility [18]. Processing techniques like milling, extrusion, fermentation, and enzymatic treatment are employed to enhance their solubility, digestibility, and sensory attributes [18].

Consumption of whole grain cereal proteins is linked to health benefits including improved lipid metabolism, reduced risk of obesity, and better blood glucose regulation [10]. Advances in cereal protein ingredients enable the development of high-protein breads, pasta, dairy alternatives, and meat substitutes, supporting dietary shifts toward plant-based eating patterns [10].

While cereals are a sustainable protein source, challenges such as allergenicity (e.g., gluten intolerance) and balancing nutrient profiles in processed foods remain. Overall, cereal proteins offer valuable potential for nutritious, functional, and environmentally friendly food applications, with ongoing research focused on overcoming current limitations to broaden their use.

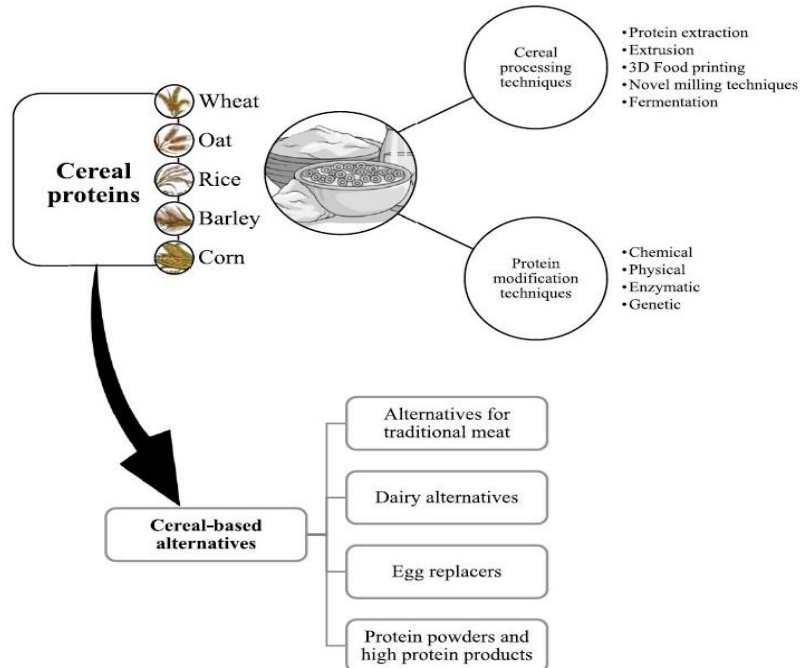


Figure 2. Processing, modification, and applications of cereal-based proteins [11]

Legume proteins

Legume proteins are increasingly recognized for their significant potential in food applications due to their balanced amino acid profiles, excellent nutritional quality, and functional properties such as emulsification, gelation, and foaming [2, 9, 19]. Prominent legumes like soy and pea offer high Protein Digestibility Corrected Amino Acid Scores (PDCAAS), comparable to animal proteins, making them valuable alternatives in plant-based foods [9, 19]. These proteins exhibit strong water and oil retention capacities, contributing to texture and stability in diverse products such as meat analogs, dairy substitutes, and baked goods [4, 9], as presented in Figure 3.

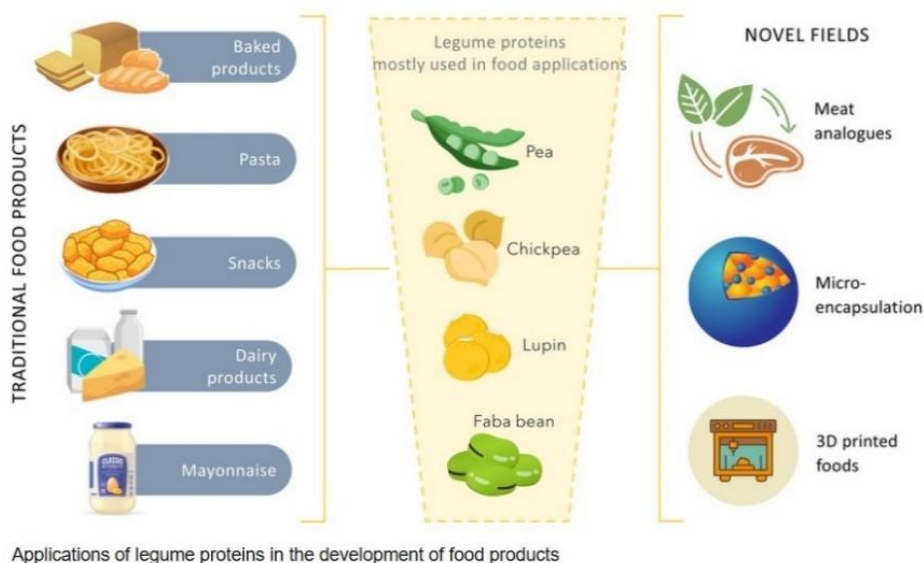


Figure 3. Applications of legume proteins in the development of food products [9]

Beyond nutrition and functionality, legume proteins are highly sustainable, generating significantly lower greenhouse gas emissions than animal proteins [1, 4]. However, challenges including limited sulfur-containing amino acids, beany flavors, and allergenic potential pose obstacles to wider adoption [1, 4, 9]. Processing techniques such as heat treatment, fermentation, and novel technologies like ultrasound treatment help mitigate these issues, improving digestibility and sensory attributes [4, 9].

Legume protein byproducts, such as seed coats and pods, are also being explored as valuable ingredients for enhancing food nutritional and functional quality in a circular economy approach [1, 9]. Continued research and innovation in extraction methods, ingredient formulation, and genetic improvement of legume crops will be essential to fully leverage their potential in developing nutritious, functional, and sustainable food products to meet growing consumer demand.

Zein

Zein is a major storage protein found in corn and is widely used in food applications due to its unique functional properties [20, 21]. It is characterized by its high hydrophobicity, making it water-insoluble but highly effective in forming films and coatings [20, 21]. This feature allows zein to be used as an edible coating for dried fruits, nuts, candies, and rice to enhance shelf life and control moisture [22].

In addition to its coating properties, zein's ability to form viscoelastic, flexible, and biodegradable films makes it valuable in food packaging as a sustainable alternative to synthetic materials [20]. Its structural properties also lend themselves to the development of plant-based meat and cheese analogues [23, 24], where zein networks can mimic certain textures of animal proteins [25].

Nutritionally, zein is somewhat limited because it is deficient in some essential amino acids [26], but it remains a valuable ingredient when combined with other proteins to improve overall quality. Zein is generally recognized as safe (GRAS) by the FDA and is commercially produced primarily as a byproduct of corn starch and syrup manufacturing [21].

Ongoing research focuses on improving zein's functional and nutritional qualities through enzymatic and chemical modifications as presented in Figure 4 and exploring its encapsulation abilities for bioactive compounds in food and pharmaceutical products [27]. Overall, zein represents a versatile, plant-based protein with increasing applications in sustainable food design and packaging.

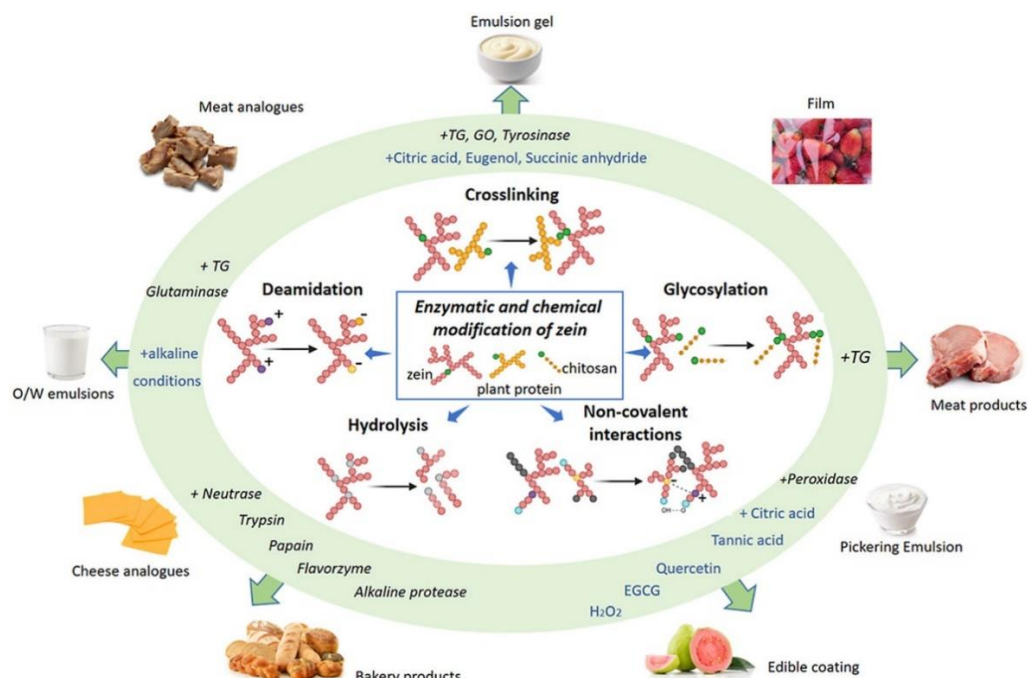


Figure 4. Modification of zein and its potential application in various food products [27]

Potato protein

Tuber proteins, such as potato protein, are gaining attention in food applications due to their unique functional and nutritional properties [17, 28]. Potato protein, primarily composed of patatin and protease inhibitors, is highly soluble and exhibits excellent foaming, emulsifying, and gelling capacities [17, 29]. These characteristics make it suitable for diverse applications including bakery products, plant-based dairy and meat alternatives, and confectionery [29], as some are shown in Figure 5. Potato protein is also allergen-free, enhancing its appeal as a clean-label ingredient [28].

Nutritionally, potato protein is rich in essential amino acids, notably lysine, making it complementary to cereal proteins which are typically lysine-deficient [17, 28, 30].

Potato protein is typically extracted as a byproduct of the starch industry, increasing its sustainability credentials [28]. However, processing methods can influence its functional performance; for example, denaturation during extraction can reduce solubility and techno-functional qualities [28].

Emerging research focuses on optimizing extraction and modification techniques to preserve or enhance potato protein's functionality [30, 31]. It is also explored as an encapsulating agent in spray drying applications due to its emulsifying and antioxidant properties [17, 32]. Overall, potato and other tuber proteins represent promising plant-based ingredients that combine high nutrition with superior functional properties, supporting their growing use in sustainable food innovation [17, 31].

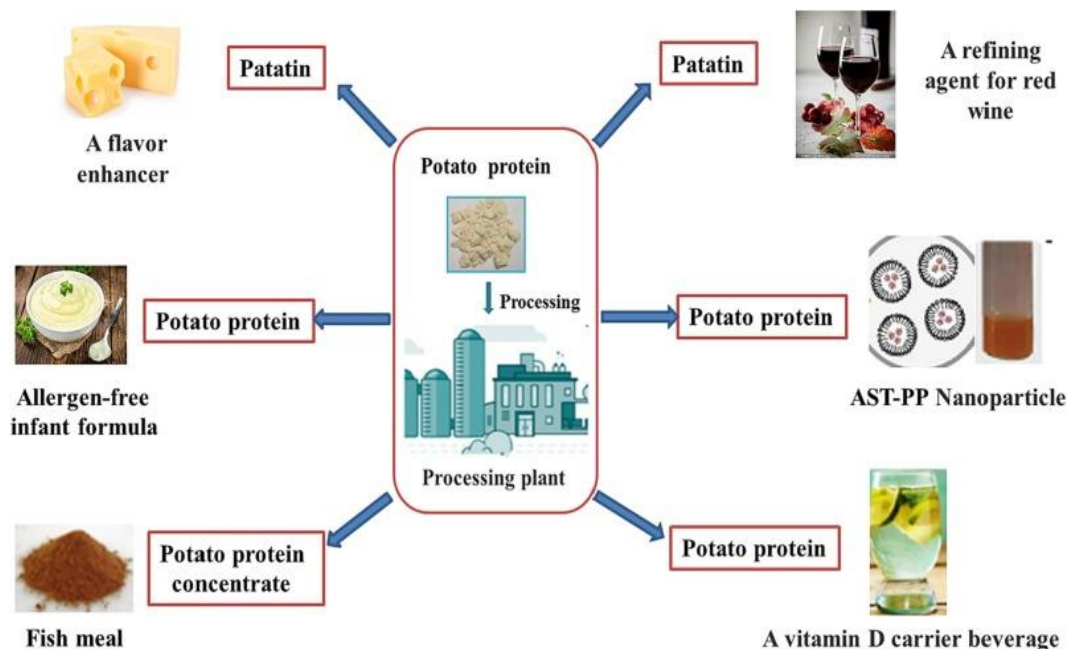


Figure 5. Potato proteins and its application in food products [31]

Oilseed and nut proteins

Oilseed proteins are increasingly valued in food applications for their high nutritional quality and multifunctional properties [13]. Oilseeds such as flaxseeds, chia, hemp, sesame, pumpkin, and sunflower are rich sources of plant-based proteins, fiber, healthy fats, vitamins, minerals, and antioxidants [13]. These proteins are often complete or nearly complete in essential amino acids, supporting balanced nutrition and serving as alternatives to animal-derived proteins [13, 14].

Functionally, seed proteins contribute to food texture, emulsification, water and oil retention, and foaming, making them versatile ingredients in baked goods, dairy alternatives, snacks, and protein-enriched foods [13, 14]. Additionally, many seed proteins exhibit bioactive properties like antioxidant, antimicrobial, and

antihypertensive activities, enhancing the health benefits of foods formulated with them [33].

Utilization of seed proteins and their hydrolysates also aligns with sustainability by valorizing byproducts and reducing food waste. Challenges include extraction efficiency, sensory concerns like bitterness, and the presence of antinutritional factors, but ongoing research explores improved processing methods to optimize their performance and acceptance [33]. General comparison of the composition and utilization between oilseeds and oilseed meals have been shown in Figure 6.

Overall, seed proteins offer promising potential as nutritious, functional, and sustainable ingredients that contribute to the development of health-promoting and environmentally friendly food products, meeting the rising demand for plant-based protein sources [13].

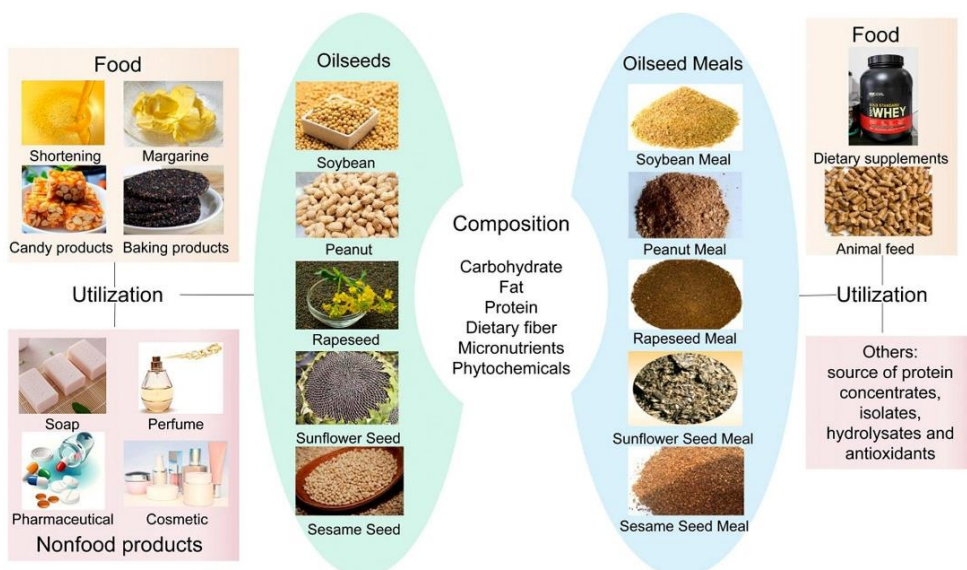


Figure 6. General comparison of the composition and utilization between oilseeds and oilseed meals. [13]

Rubisco

Rubisco (Ribulose-1,5-bisphosphate carboxylase/oxygenase) is emerging as a promising plant protein for food applications due to its excellent nutritional and functional properties such as strong emulsifying, gelling, foaming, and thickening abilities, which are valuable in formulating plant-based meat substitutes, dairy alternatives, and other food products [15, 34]. It is also non-allergenic and contains bioactive peptides with potential health benefits such as antioxidative and antihypertensive effects [15]. It is abundantly found in all green plants and photosynthetic organisms, making it a highly sustainable protein source. Rubisco contains a complete profile of essential amino acids, with digestibility and nutritional

quality comparable to animal proteins like eggs and whey, making it highly suitable for vegetarian and vegan diets [15, 16].

Functionally, Rubisco exhibits versatile techno-functional properties including emulsification, gelling, foaming, and thickening, which are valuable in formulating plant-based meat, dairy alternatives, and other food products [34, 35]. Moreover, it is non-allergenic and contains bioactive peptides with potential health benefits such as antioxidative, antihypertensive, and appetite-regulating effects [15].

Despite its potential, Rubisco's commercial use has been limited due to challenges in cost-effective large-scale extraction and purification from leafy biomass [15]. However, recent technological advancements have improved its isolation from agricultural byproducts like alfalfa leaves and vegetable wastes, enhancing its feasibility for industrial food applications [15].

Future perspectives

The future of plant proteins including cereal, legume, tuber, oilseed, nut proteins, and Rubisco holds immense promise amid growing global demand for sustainable, healthful, and versatile food ingredients. Each protein type offers unique advantages that align well with evolving consumer preferences and environmental goals but also faces specific challenges requiring continued innovation. Cereal proteins provide an abundant and cost-effective base with strong structural properties, especially gluten's elasticity, crucial for bakery and meat analog products [10, 11]. However, their limited amino acid profiles and allergenic potential (e.g., gluten) necessitate blending with other proteins and ongoing efforts to improve their digestibility and functionality [11, 12].

Legume proteins excel nutritionally with complete amino acid profiles, high digestibility, and functional attributes like emulsification and gelation [1, 4]. Flavor challenges and anti-nutritional factors remain obstacles, but advances in processing and breeding continue to mitigate these issues [1].

Tuber proteins such as potato protein are notable for their excellent solubility, emulsifying capacity, and allergen-free status [17, 31]. Being byproducts of starch industries makes them highly sustainable. Yet, sensitivity to processing conditions and limited availability constrain broader utilization, signaling a need for scalable extraction and stabilization technologies [17, 31].

Oilseed proteins are recognized for their rich nutritional content, including essential fatty acids and bioactives, adding multifunctionality to food products [13]. Their sometimes bitter flavors and antinutrients require refinement through enhanced processing and formulation strategies [13].

Zein, the corn protein, is prized for film-forming and barrier properties, supporting edible coatings and plant-based product textures [20, 21]. Its hydrophobic nature limits solubility, necessitating chemical or enzymatic modifications for versatility [20, 21]. Rubisco stands out as a sustainable, highly nutritious, and functional protein with potential to address many current plant protein limitations [15, 16]. Commercial-scale

extraction and cost remain challenges, but technological breakthroughs are rapidly making Rubisco a viable next-generation food protein [15, 34]

Overall, integrated approaches combining crop improvement, innovative processing, and hybrid protein formulations will be essential to harness the full potential of these plant proteins. This will enable the food industry to deliver nutritious, appealing, and sustainable products, meeting the increasing global protein demand while addressing health and environmental concerns.

Conclusion

Plant proteins from cereals, legumes, tubers, seeds, zein, and Rubisco offer diverse nutritional and functional benefits essential for developing sustainable and health-forward food products. While each protein source has distinctive advantages, such as complete amino acid profiles, superior emulsification, or film-forming capacities, they also present challenges including limited solubility, antinutritional factors, flavor issues, and extraction costs. Addressing these limitations through advanced processing techniques, protein blending, and crop innovation is crucial for maximizing their potential. The growing consumer demand for plant-based options and environmental sustainability drives the urgent need to refine these proteins for broader, more effective food applications. Ultimately, leveraging the complementary properties of various plant proteins will enable the creation of nutritious, appealing, and environmentally responsible foods, contributing significantly to global nutrition security and reduced ecological impact.

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BILJNI PROTEINI I NJIHOVA PRIMJENA U HRANI

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Sažetak. Cilj ovog preglednog rada je usmjeren na kritički osvrt upotrebe različitih biljnih proteina i njihovu primjenu u hrani, obuhvatajući njihove tehnofunkcionalne osobine i mogućnosti razvoja novih proizvoda. Korištene metode rada su uključivale pregled literature u posljednjih 10 godina koristeći različite naučne baze (PUBMED, SCOPUS). Biljni proteini su privukli značajnu pažnju kao održiva i zdravstveno promotivna alternativa životinjskim proteinima u prehrambenoj industriji. Biljni proteini, dobijeni iz različitih izvora kao što su mahunarke, žitarice, orašasti plodovi i sjemenke, posjeduju multifunkcionalna svojstva, uključujući emulgovanje, želiranje i sposobnost zadržavanja vode, što je ključno za formulisanje hrane. Njihova primjena podržava sve veće interesovanje potrošača za biljnim, zdravim i hranjivim proizvodima, usklađenim sa ciljevima ekološke održivosti. Međutim, izazovi i dalje postoje, uključujući nepotpune

profile aminokiselina, nižu svarljivost i senzorne probleme npr. ukusa pasulja, što može uticati na prihvatanje od strane potrošača i nutritivni kvalitet. Napredak u tehnikama ekstrakcije, modifikacije i miješanja poboljšao je funkcionalne performanse i nutritivnu vrijednost biljnih proteina, omogućavajući njihovu širu primjenu u zamjenama za meso, alternativnim mliječnim proizvodima, pekarskim proizvodima i grickalicama. Očekuje se da će buduće inovacije biti usmjerene na diverzifikaciju izvora proteina, poboljšanje teksture i ukusa proizvoda, kao i na primjenu novih tehnologija, na primjer precizne fermentacije i formulacije vođene vještačkom inteligencijom. Sveukupno, biljni proteini predstavljaju svestranu i važnu komponentu za razvoj održivih, zdravih i privlačnih prehrambenih proizvoda, doprinoseći globalnoj sigurnosti hrane i smanjenju uticaja na životnu sredinu. Kontinuirana interdisciplinarna istraživanja i saradnja industrije biće ključni za prevazilaženje trenutnih ograničenja i maksimalno iskorištavanje potencijala biljnih proteina u promjenjivom prehrambenom okruženju.

Ključne riječi: biljni proteini, hrana, nova hrana, cirkularna bioekonomija

