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Food Technology: Innovations in Plant-Based Protein Sources

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ABSTRACT

The global shift toward sustainable food systems has intensified interest in plant-based proteins as viable alternatives to animal-derived sources. This review explores cutting-edge innovations in plant-based protein technology, focusing on molecular functionality, nutritional benefits, processing methods, and consumer acceptance. Challenges related to texture, flavor, and functionality have driven significant research into protein extraction, structural manipulation, and processing techniques such as extrusion, fermentation, and high-pressure treatments. The role of legumes, pseudocereals, seaweed, and novel crops in expanding protein sources is critically evaluated. Flavor and texture optimization remain pivotal for market success, requiring an advanced understanding of protein-swelling behavior and consumer preferences. In parallel, sustainability, food safety, and regulatory frameworks are influencing the scalability and global commercialization of plant-based proteins. This paper synthesizes current trends, identifies knowledge gaps, and highlights the interplay between science, technology, and consumer dynamics shaping the future of plant-based nutrition.

Keywords: Plant-based protein, food technology, protein functionality, sustainable nutrition, protein extraction, texture optimization, novel processing.

INTRODUCTION

The growing demand for sustainable, environmentally friendly foods has sparked global interest in plant-based diets and food technologies. Plant proteins can be more environmentally friendly than animal-based options, but processing them can be challenging. The functionality of these proteins relies on their molecular properties, including structure, solubility, and viscosity. There is considerable interest in understanding plant protein functionality and the factors impacting it, spanning molecular to macroscale levels. Many food applications necessitate controlled changes in these molecular properties during processing. Traditionally, functionality has been modified using heat denaturation, fermentation, or electrostatic stabilization. Discussions will include the control of protein functionality and its implications on macroscopic properties. The benefits and challenges of plant proteins are highlighted, alongside existing knowledge gaps and ongoing research areas. While plant proteins hold potential for meat and dairy alternatives, supply chain issues hinder commercialization. Legumes are the primary focus for plant proteins, but fall short in mimicking meat or dairy products. Expanding the sources of plant proteins and developing purification technologies is crucial. The rise of protein extracts/isolates beyond conventional food inputs will challenge food safety norms. There is also potential for enhancing extraction processes by lowering costs and temperatures, thereby enabling specific protein variants or improving functionality through shearing. Significant advancements are essential to develop technologies for producing viable materials for market validation [1, 2].

Nutritional Benefits of Plant-Based Proteins

The consumption of animal-source protein is costly, contributes to environmental degradation, and is linked to health issues. Resistance to shifting towards plant-source protein persists, yet acceptance of vegetarian and vegan diets is rising. The lower production costs and environmental impact of plant-source proteins, alongside a variety of options, position them as a viable means to improve human health. This review explores current plant protein consumption patterns and suggests strategies to enhance plant protein nutrition. Dietary protein is crucial for growth and health, supplying essential amino acids (EAA) needed for metabolic functions. While animal-source protein provides all necessary EAAs due to its digestibility, its high cost contributes to greenhouse gas emissions and water depletion. Rising populations and increased animal protein consumption in developing areas pose threats to food security and climate stability. Plant-source protein, which is more cost-effective and environmentally friendly, constitutes less than 30% of total dietary protein in many regions. Growing awareness of plants as potential protein sources and the health risks associated with animal protein may drive a shift towards plant-based diets. Strategies to boost plant protein intake and availability include combining plant proteins with complementary EAA profiles, focusing on high-quality plant protein cultivation, and enhancing protein extraction methods in cooking and industrial processing [3, 4].

Current Trends in Plant-Based Food Technology

In the past decade, literature has emphasized a holistic nutrition approach in dietary patterns, linking public health with environmental sustainability. The focus is on socioculturally acceptable and affordable dietary patterns rather than single food items. Plant-based diets are increasingly viewed as beneficial for both health and the planet, as evidenced by a surge in scientific publications discussing plant-based foods, nutritional aspects, innovations, and market dynamics. Proteins, essential macronutrients made of amino acids linked as polypeptides, are crucial in food technology from both nutritional and environmental perspectives. There is a shift from traditional protein sources like milk, eggs, and meat to plant-based alternatives such as pulses, oilseeds, cereals, and pseudocereals, despite challenges associated with their protein quality and functionality. Understanding the nutritional and functional properties of these plant-derived ingredients is vital. Research aims to enhance the technological aspects of plant proteins through production phase manipulation. Literature indicates that modifying the structure of plant proteins to achieve qualities similar to animal proteins is a key challenge. With rising food demand and the need for higher-performing proteins, various treatments, both thermal and non-thermal, are being explored. Heating, a primary method, alters the functional properties of proteins by denaturing them, exposing hydrophobic groups, and forming aggregates through disulfide bonds, enhancing solubility and emulsifying abilities. Additional methods like high-pressure processing and extrusion cooking are investigated to alter protein structure while improving digestibility [5, 6].

Key Ingredients in Plant-Based Protein Products

Plant proteins are a significant alternative, representing 40% of the protein market, closely following dairy and meat. They serve as excellent supplements in various products like fortified pasta, baked goods, drinks, and meat substitutes. However, some novel plant proteins face technological, functional, and nutritional challenges. Vegetarian products are increasing, with a 5% to 30% market share, alongside seafood and dairy alternatives. Proteins, essential macronutrients in all cells, provide vital amino acids, making plant-based proteins viable substitutes. The food and feed industry seeks to enhance protein sources for better nutritional and technological quality. Recent plant-based proteins from leguminous crops possess high nutritional balance and low allergenicity, being evaluated as sources for pasta and baked items. New protein sources for aquaculture are also being researched. Additionally, the soya cheese production process yields a high-protein tofu-like by-product, containing 43.5% protein, which is safe and effectively produced [7, 8].

Processing Techniques for Plant-Based Proteins

The emergence of food processing technologies has transformed the food industry, enhancing properties like acceptability, nutritional content, safety, and shelf life. Traditional processing machinery is integrating with new procedures and control technology, leading to innovative development pathways. Current innovations focus on systematic process design and control, based on fundamentals of mass and energy transfer, moving beyond traditional methods towards a science-driven approach involving thermodynamics and biological principles. Novel techniques to analyze food structure at molecular levels are evolving, with promising technologies such as low-field nuclear magnetic resonance for moisture determination and Raman spectroscopy for structural changes detection. The development of ultrafast characterization techniques is fostering multidisciplinary approaches in food chemistry. Point-of-use solvation technology offers instant preparation of fresh ingredients. Future research should distinguish between primary and secondary post-harvest processes and confirm the scientific basis of processing technologies. Understanding the structure-function characteristics can enable the creation of functional food products aimed at weight management, cardiovascular health, diabetes control, cognitive function enhancement, and dementia prevention [9, 10].

Flavor and Texture Enhancement

With the increased concern for food sustainability, manufacturers of plant-based meat products are struggling to find the best solution to formulate protein sources, such as soy, pea, wheat, and potato proteins, to target specific flavor and texture profiles. It generally depended on proteins to deliver the functional properties to achieve flavors, textures, and mouth sensations. However, protein functionalities are extremely complex and not well understood. To overcome these hurdles, a novel approach was developed to characterize plant proteins into two main categories: heat swelling and cold swelling, while further subcategorized into four categories, including soluble, heat-swelling, and cold-swelling proteins. The objective was to determine the difference between heat swelling and cold swelling proteins when they were used to formulate meat analogue products targeting specific textures. Cooked analogues were subjected to a series of instrumental texture analyses, as well as sensory evaluations on both flavor and texture profiles. To provide a better understanding of how texture is perceived by consumers, a consumer study was conducted in conjunction with a focus group. It was hypothesized that including more cold-swelling proteins in a protein formulation would increase the softness of the product, while including more heat-swelling swelling would cause an increase in firmness. The cold-swelling proteins caused less crosslinking during heating, creating a softer texture. The extent of the heating step also played a role, as more extensive cooking processes denatured larger numbers of proteins, resulting in a firmer product. A higher percentage of cold swelling or cold swelling to heat swelling protein ratio led to an increased degree of crosslinking, greater porosity, and lower bulk density. This, in turn, led to a higher water-holding capacity in the final product. In the final product, the use of greater proportions of heat-swelling proteins led to increased texture hardness, gumminess, and chewiness, while the proportion of cold-swelling proteins had the converse effect. Unfolded proteins exposed greater amounts of polar side chains, which allowed for greater interaction among other amino acids and the formation of a large protein network. However, a higher water-holding capacity, lower bulk density, and less structural compactness or layering caused a decrease in the hardness of the product, ultimately leading to an increase in consumer liking. Overall, this research contributes to the understanding of protein functionality and proposes a novel technique to manipulate and control plant-based meat textures [11, 12].

Sustainability and Environmental Impact

Recent rising concerns about food sustainability have made plant-based foods of greater global interest. Recent trends show a deviation from red meat toward plant-based protein alternatives, such as those that utilize pea and faba beans. Although these alternatives remain some of the best substitutes on the market, they are processed by specific requirements. The production of textured pea proteins seems to be on the rise for meat alternatives as this market continues to grow rapidly. Seaweed proteins are also increasingly explored for the development of plant-based foods, as they are nutritious, renewable, and sustainable. There are significant environmental stresses associated with animal production. Livestock production may be environmentally friendly, but it is important to switch to more plant-based diets as ruminants generate two-thirds of the GHG emissions associated with animal protein production. It is important for companies to strive to improve their transparency in sourcing, processing, and delivering sustainability actions. The various plant-based proteins and how they are used in applications will be discussed in this section. It will be highlighted how a good understanding of the protein will ensure that it is perfectly processed for the first applications of meats, emulsified sauces, dairy applications, etc. Novel, exciting food applications will be shared using plant proteins with manufacturing technology to achieve the intended structure and texture. The benefits of these technologies are to reduce the exposure to chemicals and thermal conditions during processing. Some lipid sources, such as fermentation processes to stabilize plant-based oils, will also be highlighted [13, 14].

Consumer Acceptance and Market Trends

Plant-based food has been gaining momentum globally, marked by evolving consumer behaviors toward greater consumption of meat alternatives. Alongside a rise in vegan and flexitarian diets, rapidly rising interest in plant-based food in Indonesia fosters hope for solutions to climate change, international reductions in livestock protein consumption, and alternatives to meat and dairy focused on various grains and legumes. With a consumer base being updated on the nutritional and sensorial advantages of plant-based protein sources, a consumer-driven acquisition trend transformed innumerable food start-ups eager to launch novel products, which may soon become industry giants. The pandemic pushed many to prepare fresh foods, yet this means learning how to cook. Transitioning from a staple starch to a staple protein should be sensitive to current ontology and driven by acquisitions that pursue original meals. All the use-cases regarding how alternative proteins can then be integrated into meals should be validated, as they bridge product attributes, functionalities, and co-occurring ingredients, properties, and states in final foods. Continuing to solve cross-cutting issues would be a key enabler for their massive success against animal products and ultimately foster equitable protein transition. Encouraging consumers' commitment and participation in plant-based sustainability efforts drives demand; yet, plant-centric food innovation should improve value propositions. At the intersection of consistent quality disruption threat, rising ideological corporate pressure, and increasing plant-based food consumption, consumer demand is tipping for more tailored innovation. Brands can leverage preference structure, purchase behavior, and in-context first principles to better understand needs and mitigate tension, and identify opportunities for future-fit propositions. A value proposition model encompasses involuntary uniqueness to assess value creation decisions post-disruption and is demonstrated with dairy-free yogurt and peanut butter. Solutions that reduce spillage, substitute protein intake, or bypass current offerings' sizing or cold chain needs indicate demand for a product-customized approach [15, 16].

Regulatory Considerations

Concern about natural resource depletion, climate change, animal welfare, and public health is growing. Considering the current world population of 6.9 billion inhabitants and the food security awakening throughout the world, the availability and distribution guarantees regarding the most consumed food sources (meat, dairy products, fish, and eggs) are worrying not only the countries with a lower human development index but also the wealthier countries. Such awareness drives the search for new sustainable protein sources. The most prominent new protein sources include the unconventional use of crop plants (such as legumes, oilseeds, kernels, pseudocereals, roots, shoots, and grasses), fungi, algae, and insects. Food-grade insects are excellent protein sources, containing around 25-60 g of protein per 100 g of fresh food, and their protein digestibility correct digestibility values are also high (around 35 percent). However, the consumption of insects for food is not widely accepted by consumers. Therefore, among the new protein sources, plant-based protein sources draw the most attention. As for food-grade plant materials, soy and wheat gluten proteins are the most significant protein sources for the rapidly growing vegetarian food market. In addition to the classic methods, the production of textured soy proteins based on great advances in thermodynamics, kinetics, and polymer science principles is essential. However, such food materials have led to controversy regarding longitude level, reasonability, evaluation process, path, and health and nutritional aspects. The presence of attached antinutritional factors has always been the primary factor for pre-processing, including quasi-natural products such as tubers and peanuts. To obtain a well-defined molecular weight and geometric-spatial distribution of legume proteins, semi-synthetic treatments such as surfactant treatment, enzymatic treatment, reaction under controlled pH and ionic strength, changing amino-acid constitution, solubilizing-polymerizing re-/co-extruding, reducing disulfides accordingly, and treating with organic solvents need to be utilized. Evaluating and developing integrated non-thermal and thermal processing methods aims to broadly extend the plant protein utilization spectrum and improve processing efficiency [17, 18].

Challenges in Plant-Based Protein Development

Proteins are essential macronutrients, providing the necessary amino acids for health. They are composed of amino acids and categorized into two groups based on origin: animal proteins from animals and vegetable proteins from plants. Plant protein sources come from seeds, tubers, or starches, including corn gluten meal, cottonseed, chickpea, guar, pea protein concentrates, soy proteins, potato, and cassava. Dietary proteins account for 20% of daily caloric intake, averaging about 60 g for adults, varying with diet types—lower in vegan/vegetarian diets (around 40 g) and higher in meat-rich Western diets (over 50 g). The growing global population raises demand for sustainable protein sources, with non-conventional options like plants, fungi, algae, and insects emerging. The consumption of insect protein raises concerns due to deviating from traditional food production, necessitating socio-economic adaptations. This has spurred research into protein extraction, structure, and functionality during food processing and digestion. Many new products focus on extracting valuable compounds from plant and animal by-products. This mini-review discusses food-grade insect proteins, highlighting their significance for food safety regulations and protein solubility in the industry. It includes information on the hydrolysis processes of insect chitin from dormouse carcasses using subcritical and microwave-assisted methods. The chemical composition, structural changes, amino acid sequences, and bioactive properties of hydrolyzed insect proteins are outlined, demonstrating improved solubility and water-holding capacity without toxicity. Hydrolyzed insect proteins show greater in vitro antioxidant activities and α-glucosidase inhibition compared to goose and chicken proteins, indicating their potential as functional food ingredients [19, 20].

Case Studies of Successful Plant-Based Products

The world is undergoing a cultural and nutritional transformation with increasing interest in a plant-based diet. The global meat and dairy consumption per capita is increasing, accompanied by a growing awareness of its adverse impacts on human health and sustainability, resulting in a demand for novel food products. Therefore, high-quality protein sources alternative to meat and dairy have received global attention. Protein from legumes, grains, oilseeds, and other plants has been consumed as food for millennia. The production of protein and other plant-based foods using novel processing methods has recently rekindled interest due to consumer demand for sustainability, safety, and food waste reduction. This growing interest has diversified globally into several segments, including dairy alternatives, meat alternatives, egg alternatives, and broader plant-based foods, among others. In addition, advances in technology and ingredient space have fueled a booming industry with significant investment and research interest in food technology, processing technology, and product innovation for plant-based protein foods. The innovation and launch of revolutionary plant-based foods and novel processing approaches have been covered in food science, nutrition, engineering, marketing, and industry reports. Several case studies of successful plant-based protein food products worldwide, particularly synthesized from protein-rich plants using innovative ingredients and processing methods. Why some plant-based protein food products succeed, why some fail (in terms of adoption, sales, and engagement), which ingredients and processing technologies are behind the successful products, and where the industry is headed in the next decade. Since protein from plants is expected to be the primary ingredient, this could largely influence the success of the product. Soy foods and isolates are the most adopted and highly consumed plant-based food proteins globally. Besides soy protein, pulse protein is an exciting ingredient with a company exploring it in its formulation for product innovation and customer engagement in differentiating its unique contents. Pea protein, as the second most widely used ingredient, has a lot of successes and a bright future [21, 22].

Future Innovations in Plant-Based Proteins

Nutritional quality, techno-functional properties, and safety have an essential role in plant proteins' future applications. So, technologies that favorably impact these factors and could influence food composition, food structure, and food sensory properties should be developed. On the contrary, technologies that adversely influence these factors and eventually negatively impact the following food properties should be avoided. Last but not least, the feasibility of raw plant ingredients/process innovation should be analyzed. Economic, environmental, and food security issues should be taken into consideration to supply enough protein to feed the growing global population. Regarding the aspects related to the nutritional quality of plant proteins, it is currently established that proteins can form dietary protein–anti-nutritional factor complexes, such as phytates, a major anti-nutritional factor for plant proteins. Such complexes can, among other things, affect the techno-functional properties of proteins, which determine their applications in food products. For example, soluble proteins are essential for stabilizing dairy emulsions, while gelling proteins are critical for the functionalization of meat alternatives. Therefore, developing new technologies to offer adequate ways of processing protein-containing plant materials will not be enough to guarantee the successful future applications of plant proteins. The structural and compositional properties of proteins determine their nutritional quality and the techno-functional properties that contribute to appreciating the food composition and structure, and the final sensory and textural products. Folate is relevant for a wide range of physiological functions, depending on cellular processes of nitrogen-based compounds, for which the availability of some as well as the return of folates are influenced by the technological treatment of legumes. Protein extraction from legumes should avoid high temperatures to preserve folate levels. The techno-functional properties of legume proteins relevant for foaking purposes are affected by their MoFs and, irrespective of the soM, also depend on the inherent pH. However, they are largely preserved upon alkaline extraction, and their techno-functional properties can also be improved by heat treatment. The techno-functional properties of legume proteins decrease significantly at pH <5 and much less at pH >8 [23, 24].

Global Perspectives on Plant-Based Diets

Human beings, like all animal species, are primarily made up of proteins that play crucial roles in metabolism and serve as essential macronutrients in nutrition by providing amino acids. Recent concerns about the negative impacts of animal protein production on health, resource depletion, climate change, and animal welfare have led many Western societies to adopt vegetarian and vegan diets, reducing animal product consumption. This trend appears to fluctuate, with periods of rapid growth followed by years of consolidation and reassessment. The increasing global population drives interest in sustainable protein sources to meet rising demand. Among these new sources, non-conventional plants, fungi, algae, and insects have emerged, with plant-based proteins being particularly prominent. The nutritional quality of proteins, vital for the technological processing of protein-rich materials, has been a significant focus of research. Studies have examined the effects of various physical processing technologies on plant proteins, which are typically extracted using aqueous, thermal, and particulate methods. Key steps include separation and concentration, often utilizing gel filtration and ultrafiltration. Food processing is deemed essential for enhancing the nutritional quality and functionality of plant proteins. Generally, thermal processing increases the nutritional value by deactivating anti-nutritional compounds, thereby improving digestibility. Additionally, many emerging processing technologies have gained attention in the last two decades for their potential to effectively utilize protein-rich materials [25-30].

Culinary Applications of Plant-Based Proteins

Peas, beans, lentils, soybeans, and tubers (potato, yam, cassava, etc.) are the primary sources of plant protein ingredients. These vegetable protein origins have been recognized in the scientific literature and have been researched for many years. However, the food industry has only recently utilized these plant sources with a high protein content as ingredients to produce plant-based protein products. Some sources are considered complementary. For example, the consumption of cereals and legumes together is suggested to balance the essential amino acids needed by the human body. Food processing techniques, including filtration, extraction, spray drying, dry heating, and extrusion, are used to produce plant-based protein powders or concentrates. Many food products on the market primarily contain plant-based proteins. Tempeh, a product that originated from Indonesia, is one of the fermented foods made from soybeans. Formation of soybean filaments or a tofu-like structure occurs as soybeans ferment. Tempeh has superior nutrition over tofu and is manufactured in many countries, including the U.S.A. Prepping describes the extraction of thinner soy protein filaments using special machinery for making extruded nugget products. Pea pulps from protein extraction plants are graded and tested with sensors to select coloration for addition to dough. The concept of enhanced bread is to keep protein concentrated in the crust, providing a sensory contrast between crust and crumb. Ultra-processed soy milk and concentrated soy yogurt products are examples of dairy alternatives. UHT sterilization affords shelf-stable/ambient temperature storage without preservatives. Enzymes are used to coagulate milks for yogurt production, followed by UHT/Bake sterilization for shelf-stable or chilled product distribution. Dairy alternatives may contain texturized vegetable proteins, vegetable fats, thickeners, and flavor variants. High-protein snacks are conventionally made from puffed grains, but are currently reformulated with protein concentrates. Soy protein gels with filament-forming properties are now coated on chickpeas, dried, and fried for a puffy/airy structure. Pea protein concentrates & hydrolysates/spices with flavoring compounds are extruded into a brownish puffed/rigid product with a crunchy texture. The meat analogs category consists of burger patties, sausages, and nuggets formed from pre-gelled starch, tempura, and gelatin/pectin edible coating. Textured vegetable protein (TVP) is widely used to produce meat alternatives [31, 32].

CONCLUSION

The advancement of food technologies has positioned plant-based proteins at the forefront of sustainable dietary innovations. While significant progress has been made in improving protein extraction, functional properties, and processing techniques, challenges remain in replicating the sensory attributes of animal proteins. Addressing these challenges requires interdisciplinary research and collaboration across food science, biotechnology, and consumer behavior. The expansion of plant protein sources and the development of tailored processing methods are crucial for delivering nutritious, palatable, and sustainable food products. Furthermore, aligning regulatory frameworks with scientific innovation will enable broader market adoption and trust in plant-based alternatives. As consumer awareness and demand continue to rise, plant-based protein technologies offer promising pathways for improving global health, environmental sustainability, and food security.

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