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Review Paper

Valorization of plant-based agro-industrial residues for recovery of bioactive peptide-rich fractions and their application in muscle foods

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A B S T R A C T

Plant-derived protein hydrolysates are gaining increasing attention as sustainable sources of bioactive peptides with functional and health-promoting properties. This review highlights the potential of utilizing agro-industrial by-products as substrates for producing bioactive peptide-rich hydrolysates and explores their applicability in muscle-based food formulations. Enzymatic hydrolysis is the most commonly used method for obtaining these fractions, offering a green and efficient strategy for valorizing plant-based waste. Various studies have demonstrated that such hydrolysates can enhance bioactivities, improve techno-functional characteristics, and contribute to the overall quality and shelf life of meat products. Specifically, protein-rich residues from plant processing, such as oil cakes, brans, and other wastes, offer the dual benefit of supporting clean-label food formulations while reducing environmental impact through waste valorization. Overall, protein hydrolysates of these sources represent a promising class of natural ingredients for the reformulation of healthier and more sustainable meat products.

1. Introduction

Bioactive peptides (BPs) are defined as food components encoded within the primary structure of proteins, which, upon release, exert effects on biological processes and substrates, thereby providing beneficial impacts on body functions and overall health (*Bhat et al.*, 2015; *Singh et al.*, 2022). Bioactive peptides have been reported to exhibit a wide range of physiological effects, including antithrombotic, antihypertensive, antioxidant, antibacterial, immunomodulatory, anticancer, and cholesterol/ blood pressure-lowering properties.They have been shown to impact not only human health but also the sensory and functional quality of food products (*Toldrá et al.*, 2020; *Du and Li*, 2022; *Singh et al.*, 2022; *Karami and Akbari-Adergani*, 2019). Due to these positive impacts and their origin from highly biocompatible sources, BPs are considered promising compounds with potential applications in food, medicine, pharmaceuticals, cosmetics, and various other fields (*Akbarian et al.*, 2022). There is a growing global interest in BPs derived from food proteins, with the market value estimated at USD 48.6 billion in 2020 and projected to reach USD 95.7 billion by 2028 (*Du and Li*, 2022). It is well established that various plant- and animal-based foods contain signif-

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icant amounts of BPs. In addition to meat- and milk-derived BPs, plant-based sources such as legumes, cereals, fruits, and seeds have also been reported as important reservoirs (*Singh et al*., 2022). Beyond their beneficial effects on health, plant-derived biopeptides are emphasized as more accessible, sustainable, and cost-effective sources compared to those of animal origin (*Akbarian et al*., 2022; *Singh et al*., 2022). Therefore, investigating the isolation of plant-based BPs from alternative sources and their application in food formulations represents a highly relevant and valuable research area.

The agri-food industry generates large volumes of by-products and waste at both on-farm and off-farm levels. Accounting for nearly 50% of total agricultural output, these wastes pose challenges in safe disposal and contribute significantly to environmental pollution (*Ben-Othman et al*., 2020). According to the United Nations Environment Programme (UNEP) Food Waste Index Report 2024, 19% of food available to consumers is wasted globally, totaling 1.05 billion tons per year across retail, food service, and households. More than half of it originates from households- equivalent to over one billion meals discarded each day worldwide. Another striking finding from the report is that approximately 60% of all food waste consists of plant-based food products, highlighting the critical need for valorizing plant-derived residues in sustainable food systems (*UNEP*, 2024). This context underscores the importance of developing value-added strategies for the utilization of plant-based food residues, particularly through the recovery of functional components such as protein hydrolysates.

Based on these insights, this review aims to highlight the potential use of plant-derived protein hydrolysates in muscle food formulations, with a specific emphasis on the by-products as sustainable sources of bioactive peptides.

2. Obtaining biopeptide-rich fractions from plant-sourced proteins

BPs can be derived from various plant sources such as legumes, seeds, nuts, cereals, and fruits through processes like enzymatic hydrolysis, fermentation, and other extraction techniques. Among these methods, enzymatic hydrolysis is the most commonly applied approach, as it enhances the nutritional and functional quality of protein sources. It is considered as safe and environmentally-friendly green technique due to the absence of residual organic solvents or toxic chemicals during the reaction process (*Angulo and Márquez*, 2023). In common applications of enzymatic hydrolysis, one or more proteases are employed to break down proteins into smaller peptides and free amino acids. The resulting fraction, known as the "hydrolysate", primarily contains dipeptides and tripeptides, which often exhibit enhanced bioactivities and functional properties compared to the parent protein chain (*Eckert et al*., 2019; *Zinina et al*., 2022). Figure 1 presents the main steps of the production of plant protein hydrolysates and bioactive peptides through enzymatic hydrolysis. The steps mainly cover the application of pre-treatments in the raw material, enzymatic hydrolysis application, protein separation and purification, assessment of bioactivity, identification of peptides in the sub-fractions, and verification of bioactivity after chemical peptide synthesis (*Ozturk-Kerimoglu et al*., 2025). One major challenge in working with plant protein hydrolysates is the presence of impurities such as fibers and non-protein compounds, which may compromise peptide quality and safety; thus, effective protein purification is essential. Several techniques such as membrane filtration, gel permeation chromatography, ion-exchange chromatography, and reverse-phase high-performance liquid chromatography (HPLC)

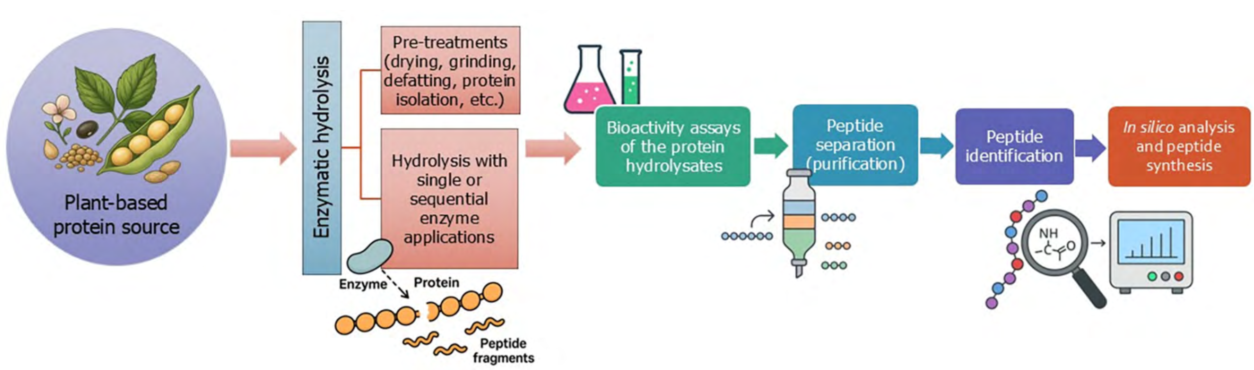

Figure 1. Key steps in obtaining plant-based protein hydrolysates and bioactive peptides through enzymatic hydrolysis

can be employed for the purification process, each offering distinct advantages depending on the properties of the hydrolysate and the specific goals of the process (*Kadam et al*., 2024).

2.1. Plant-derived by-products as potential sources of functional protein hydrolysates

As mentioned above, the processing of food raw materials such as fruits, vegetables, seeds, and nuts generates a substantial amount of valuable residual fractions. Valorizing these residues, particularly those with high protein potential, through various approaches and converting them into novel food ingredients is of critical importance for sustainability. In this context, several studies have focused on the utilization of certain plant-based production wastes by transforming them into protein hydrolysates. For example, *Zaky et al*. (2019) reported that the hydrolysate obtained from the protein concentrate of rice bran (a valuable by-product of rice) digested with Flavourzyme contains bioactive components which can act as natural antioxidants in food applications. *Ospina-Quiroga et al.* (2022) investigated the physical and oxidative stabilities of simple oil-in-water emulsions containing protein hydrolysates from olive seed, sunflower, rapeseed, and lupin meals. They found out that all the emulsions were physically stable, and the hydrolysates could be successful candidates to retard oxidation in food emulsions as natural antioxidants. Another study was carried out by *Ahmed et al*. (2023) on protein hydrolysates derived from orange peel using *Aspergillus niger* WA 2017 protease, where it was reported that exhibited strong antioxidant and antitumor activities, with optimized conditions significantly enhancing DPPH radical scavenging capacity and reducing Ehrlich Ascites Carcinoma cell viability by over 60% *in vitro*, while also increasing the life span of tumor-bearing mice *in vivo*. *Zeng et al*. (2025) applied a bacterial-enzymatic co-fermentation to palm kernel cake, and concluded that this application significantly improved the nutritional quality by reducing fiber, increasing protein solubility, and releasing sugars. This pretreatment also enhanced *in vitro* intestinal digestibility and beneficially modulated gut microbiota, highlighting its potential for broader application of this by-product in animal feed production. Collectively, these findings demonstrate the growing potential of plant-based by-products as valuable sources of protein hydrolysates with diverse functional and biological activities, supporting their integration into both food and feed systems as part of sustainable and health-oriented formulation strategies.

3. Applications of hydrolysates obtained from plant-derived proteins and/or by-products in meat product formulations

The utilization of bioactive peptide-rich protein hydrolysates in various food systems is a relatively new and actively evolving research area. Due to their high biological activity, low toxicity, and ease of metabolism in the human body, there is a growing interest in food-derived bioactive peptides for the development of functional food formulations (*Singh et al*., 2022). This approach is particularly prominent in muscle-based foods. In the production of processed meat products, a variety of ingredients and additives are used for different purposes; however, in recent years, synthetic additives have increasingly been replaced with more natural alternatives in response to shifting consumer expectations. When evaluating strategies for designing healthier meat formulations, one key approach is the enhancement of product quality through the incorporation of natural and functional additives (*Ayuso et al*., 2025). In this context, the use of plant-based protein hydrolysates in various meat products has emerged as a promising strategy.

Studies involving the use of various plant-based protein hydrolysates in meat product formulations and their key findings are presented in Table 1. As seen in the table, various plant protein sources such as chickpea, mung bean, soybean, red lentil, broad bean, pea, pumpkin seed, rapeseed, and rice berry have been investigated for their potential use in meat products or animal cell culture systems. These types of hydrolysates have been shown to enhance bioactivities -particularly antioxidant activity- as well as techno-functional properties. Evaluating the applications of plant-based hydrolysates obtained from by-products, it is observed that some valuable residues, such as canola meal (*Mirzapour et al*., 2022) and tea waste (*Zhao et al*., 2014), have been utilized in meat systems as antioxidant and emulsifying agents, demonstrating their broad application potential. Moreover, it has become evident that plant-derived food industry residues are being explored for even more innovative purposes in meat systems. For example, *Flaibam et al.* (2024) reported that protein-rich extracts and hydrolysates derived from plant-based agro-industrial waste, particularly soybean and peanut meals, represent a promising and cost-effective alternative in cultured meat production. Overall, these findings highlight the growing potential of plant-based protein hydrolysates, specifically those derived from agro-industrial by-products, as multifunctional ingredients in both conventional and cell-based meat systems, aligning with current demands for health-oriented, sustainable, and clean-label food solutions.

Table 1. Applications of plant-based protein hydrolysates in meat systems

Hydrolysate material	**The applied enzyme(s)**	**Meat system**	**Key findings**	**Reference**
Soy protein	Microbial-derived extracellular protease	Pork and fish model meat system	• It was reported that hydrolysates slowed down the formation of secondary oxidation products, suggesting their potential use as natural antioxidant sources for controlling lipid oxidation.	*Oliveira et al.* (2014)
Tea dreg	Alcalase®, Neutrase®, Protamex®	Chicken patties	• Hydrolysates produced using Protamex® have been shown to exhibit high in vitro antioxidant activity and to exert antioxidant effects in liposome–meat model systems. The importance of identifying specific peptides at this stage has been emphasized. • Formulation of chicken patties with hydrolysates resulted in reduced peroxide and TBARS values.	*Zhao et al.* (2014)
Canola meal	Alcalase® and Flavourzyme®	Chicken nugget	• Alcalase-produced canola protein hydrolysate (CPH) showed higher antioxidant activity and protein recovery. • Composite coating plus CPH reduced oil uptake and increased moisture and frying efficiency. • CPH-treated nuggets had longer shelf life and delayed oxidation.	*Mirzapour et al.* (2022)
Chickpea, mung bean, soybean, red lentil, broad bean, pea, pumpkin seed, rapeseed	Trypsin and carboxypeptidase B	Animal cell culture medium	• Specifically, chickpea protein hydrolysates were developed as novel microcarriers for cultured meat applications. • The microcarriers demonstrated enhanced cytoaffinity, supporting cell attachment, proliferation, and differentiation into muscle and fat cells. • Improved cell compatibility was attributed to the exposure of lysine and arginine residues, offering a scalable and cost-effective substrate for cell-based meat production.	*Kong et al.* (2023)
Soybean meal and peanut meal	Alcalase™ 2.4 L	Animal cell culture medium	• Soybean and peanut bran were processed to obtain protein-rich hydrolysates as plant-based alternatives to fetal bovine serum (FBS). • The hydrolysates showed comparable protein profiles to FBS and contained high levels of leucine and proline, supporting *in vitro* cell growth and viability. • This approach offers a cost-effective strategy to reduce dependence on animal-derived components in cultured meat production.	*Flaibam et al.* (2024)
Rice berry and mung bean	Bromelain and Protease FP51®	Pork meat batter	• Rice berry and mung bean hydrolysates bound to protein particles at the microstructural level. • These plant proteins had limited impact on texture but may influence color when combined with bromelain. • Meat batters with 1.0% κ-carrageenan and plant proteins showed improved cooking loss and sliceability.	*Saengsuk et al.* (2024)

4. Conclusion

The focus on plant-derived, biopeptide-rich protein hydrolysates underscores a broader industry trend toward incorporating sustainable and functionally active ingredients in food systems. Particularly when derived from agro-industrial by-products, these hydrolysates offer a valuable opportunity to address both environmental and health-related challenges. Their demonstrated bioactivities and techno-functional contributions in meat systems support their integration into clean-label product development. These hydrolysates also show great promise in the field of cultured meat production, offering a sustainable and bioactive alternative for supporting cell growth and functionality. As research continues to uncover new bioactivities and optimize hydrolysate production methods, plant-derived protein hydrolysates are expected to play an increasingly important role in the formulation of next-generation, health-oriented muscle foods.

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