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Advances in protein-based functional instant beverages: Focus on soy protein isolate and collagen hydrolysate

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ABSTRACT

This review synthesizes advancements in soy protein isolate (SPI) and collagen hydrolysate (CH) instant beverages, covering their molecular structures, techno-functional properties, and health benefits. SPI, rich in globulins, offers emulsifying, gelling, and water-binding capabilities, along with cholesterol-lowering isoflavones and hypotensive peptides. CH, from bovine, porcine, and marine sources, provides low-molecular-weight di- and tripeptides (glycine, proline, hydroxyproline) with antioxidant, ACE-inhibitory, anti-inflammatory, and skin-health benefits. Their combination creates a nutritionally complete matrix with enhanced colloidal stability, thermal resilience, and broader bioactivity by complementing each other's amino acid profiles. This review addresses the instability of protein systems at varying pH and ionic strengths, and the bitterness and hygroscopicity of hydrophobic peptide fractions. To overcome these issues, we evaluate processing and stabilization strategies, including enzymatic hydrolysis optimization, high-pressure homogenization, ultrasound-assisted modification, Maillard conjugation, and advanced microencapsulation (e.g., Pickering emulsions, proliposomes, layer-by-layer coating). These technologies enhance solubility, minimize off-flavors, and preserve peptide bioactivity during digestion and distribution. The review also covers the role of packaging and storage (water activity, barrier films, controlled atmosphere) in maintaining the functional integrity of SPI-CH powders. Finally, we examine the intersection of sustainability, clean-label expectations, and regulatory compliance, focusing on valorizing animal by-products for a circular economy.

Keywords: Soy protein isolate, Collagen hydrolysate, Functional beverages, Instant powders, Bioactive peptides.

INTRODUCTION

The modern beverage sector is expanding due to manufacturers focusing on healthy formulations for weight management, cognitive enhancement, and digestive wellness (Corbo *et al.* 2014; Bogue & Troy 2016). Liquid delivery systems offer a convenient way to incorporate bioactive compounds like vitamins, minerals, and probiotics. However, developers face challenges including ingredient stability, sensory optimization, and regulatory compliance. This review examines protein enrichment and bioactive supplementation, synthesizing processing advancements to maintain ingredient viability and shelf-life(Corbo *et al.* 2014; Bogue & Troy 2016). The growing preference for plant-based and non-dairy alternatives requires understanding how these protein sources interact with functional additives to meet diverse lifestyle and ethical demands (Sharma *et al.* 2024).

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The modern beverage sector is expanding due to manufacturers' focus on health-oriented formulations that address consumer needs like weight management, cognitive enhancement, and digestive wellness. This growth is driven by the convenience of liquid delivery systems, which efficiently incorporate bioactive compounds such as vitamins, minerals, and probiotics (Corbo *et al.* 2014; Bogue & Troy 2016). However, developers face challenges including ingredient stability, sensory optimization, and regulatory compliance for health claims. This review examines protein enrichment and bioactive supplementation, synthesizing processing advancements that maintain ingredient viability and shelf-life stability (Corbo *et al.* 2014; Bogue & Troy 2016). The rising preference for plant-based and non-dairy alternatives also requires understanding how these protein sources interact with functional additives to meet diverse lifestyle and ethical demands.

Protein-enriched instant powders offer a convenient, shelf-stable, and portable nutritional supplement, addressing logistical challenges of ready-to-drink formats and meeting consumer demand for on-the-go options (Kaur *et al.* 2024). These formulations benefit diverse groups, including athletes, the elderly, and those with dietary restrictions, by providing accessible, high-quality nutrients. Functional beverages incorporating these proteins also deliver bioactive compounds with health benefits beyond basic nutrition, such as anti-inflammatory and antioxidative effects (Corbo et *al.* 2014; Dahiya *et al.* 2023). Furthermore, using plant-derived protein matrices in these beverages contributes to food security, sustainability, and ethical animal welfare, reducing the beverage industry's environmental footprint while maintaining high nutritional value (Arbach *et al.* 2021).

This review synthesizes recent advancements in protein-based beverage fortification, focusing on the synergistic integration of soy protein isolate and collagen hydrolysate to optimize sensory quality and nutrient bioavailability. It also explores how innovative processing techniques and stabilization strategies, like Pickering emulsions, overcome technical hurdles such as protein sedimentation and flavor degradation. By evaluating the interplay between physical structural stabilization and nutritional performance, this synthesis provides a framework for developing next-generation functional powders that meet clean-label expectations.

2. Soy protein isolate in functional beverages

2.1 Composition and functional properties

Soy protein isolate is characterized by a high concentration of globulin proteins, which provide essential techno-functional attributes including emulsification, gelation, and water-binding capacity. These molecular characteristics allow for the development of stable suspensions, although achieving optimal solubility across varying pH levels and ionic strengths remains a critical factor for maintaining uniform texture in commercial applications. To mitigate limitations in solubility and sensory appeal, recent research highlights the integration of enzymatic hydrolysis, which can significantly enhance the functional profile of these isolates. Furthermore, the use of these plant-based isolates as natural emulsifiers offers a clean-label alternative to synthetic additives, provided that processing conditions are optimized to maintain the structural integrity of the protein matrix (Kim *et al.* 2020; Yang 2023; Grosso *et al.* 2025). The inherent nutritional quality of soy protein is often emphasized by its balanced amino acid profile, which is comparable to bovine milk proteins. However, soy proteins are susceptible to denaturation and aggregation in acidic or high-ionic-strength environments, which can negatively affect their overall performance (Qiu *et al.* 2025). To address these technical barriers, modifications such as glycosylation have been shown to improve solubility, thermal stability, and emulsifying capacity without compromising the protein's native bioactivity (Chen *et al.* 2024).

Fig. 1 shows that soy protein isolate (SPI) is mainly globulin proteins like β-conglycinin (7S) and glycinin (11S), making up 55–70% of its total protein. These proteins give SPI its functional properties, such as emulsification, gelation, foaming, and water-binding. Albumins (20–25%) enhance solubility, while minor components (5–10% each) like glycinin-associated peptides and low-molecular-weight proteins may affect antioxidant activity and protein interactions. SPI's composition and amino acid profile are crucial for its use in protein-enriched beverages.

Soy Protein Isolate (SPI) exhibits high nutritional quality, with essential amino acids comprising 41% of its total amino acid composition, comparable to bovine milk proteins. Leucine and lysine are abundant, supporting muscle protein synthesis and metabolic regulation. However, SPI is limited by lower concentrations of sulfur-containing amino acids like methionine and cysteine.

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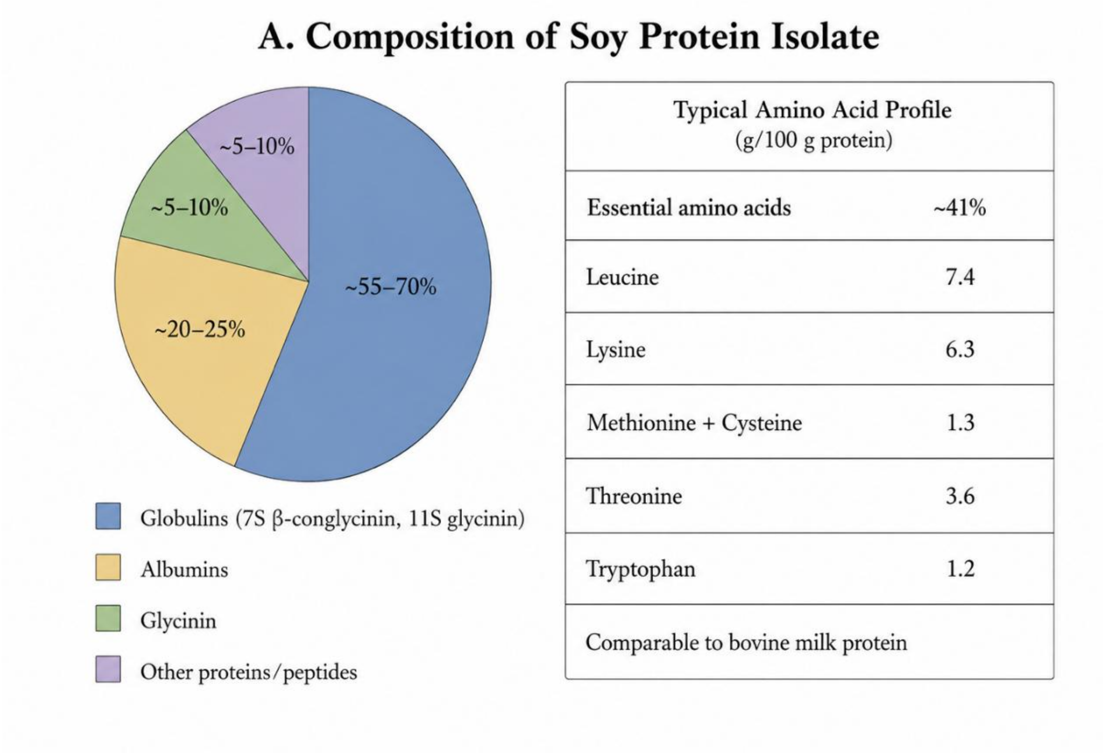

Fig. 1. Composition and amino acid profile of soy protein isolate used in functional beverage systems.

Technologically, SPI's high globulin content aids in forming stable emulsions and protein networks in beverages. Yet, these proteins are sensitive to pH, ionic strength, and heat. Acidic conditions or high mineral concentrations can cause denaturation and aggregation, reducing solubility and leading to sediment.

Thus, SPI's composition and amino acid balance are crucial for its nutritional value and physicochemical functionality, especially in developing stable, high-protein instant beverages.

2.2 Health benefits soy protein isolate in functional beverages

Beyond their fundamental nutritional utility, these proteins exert significant physiological effects, including cholesterol-lowering properties and potential protective actions against metabolic conditions such as diabetes, obesity, and certain chronic renal pathologies. Specifically, the consumption of soy-derived bioactive components has been linked to the modulation of hyperlipidemia and a reduction in the overall risk factors associated with cardiovascular disease (Tomadoni et al. 2020, Yoo & Chang 2016). Furthermore, the removal of anti-nutritional factors during the isolation process, particularly through the precipitation methods used to obtain these isolates, enhances the bioavailability of essential minerals such as zinc and copper. Additionally, the absence of cholesterol combined with a rich supply of essential amino acids makes soy protein an ideal, sustainable alternative for consumers seeking effective management of metabolic health markers. Moreover, enzymatic hydrolysis of these proteins yields bioactive peptides that demonstrate anti-inflammatory and antihypertensive activities, further broadening their therapeutic potential in functional beverage applications. Clinical evidence underscores that consistent intake of these soy proteins is associated with a lower incidence of chronic conditions, supported by high protein digestibility-corrected amino acid scores. In addition, the presence of specific isoflavones and lecithins within these isolates provides supplemental metabolic advantages that further enhance the overall health-promoting profile of soy-based formulations (Liutkevičius *et al.* 2016; Olías *et al.* 2023).

2.3 Challenges in beverage formulation

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The primary obstacle remains the inherent poor solubility of soy protein isolate near neutral pH, which frequently triggers protein-protein aggregation and sedimentation in complex beverage matrices (O′ Flynn et al. 2021). Furthermore, the interaction between soy proteins and minerals such as calcium in liquid systems often exacerbates these aggregation processes, thereby restricting their successful incorporation into ready-to-drink formulations (Manassero *et al.* 2019). To mitigate these stability issues, emerging non-thermal technologies like high hydrostatic pressure have shown promise in reducing the degree of protein aggregation, thereby improving dispersion stability in mineral-fortified systems (Manassero *et al.* 2015). Additionally, mechanical treatments such as sprouting have emerged as effective non-thermal strategies to reduce beany off-flavors and phytic acid levels without requiring the intense heat-induced degradation that can diminish native nutritional content (Sethi *et al.* 2016).
Advanced homogenization techniques further mitigate these challenges by reducing particle size and lipid droplet distribution, which fundamentally enhances the homogeneity and physical stability of the final beverage system (Tangyu et al. 2019). Ultimately, the integration of these sophisticated processing methodologies addresses critical sensory and stability barriers, ensuring that high-protein soy beverages maintain both consumer-demanded aesthetics and nutritional integrity (Tangyu *et al.* 2019; Deng & Kim 2024).

Collagen hydrolysate: Structure and bioactivity

3.1 Sources and production

Collagen is predominantly sourced from bovine, porcine, and marine by-products, utilizing controlled enzymatic hydrolysis to break down long-chain polypeptides into bioactive di- and tripeptides. These smaller fractions exhibit enhanced solubility and superior absorption kinetics compared to native collagen, which is critical for their incorporation into high-clarity, stable instant beverages (Hernández-Ledesma *et al.* 2011). Recent advancements in extraction techniques now allow for the recovery of collagen from marine sources, such as salmon scales, which effectively maintain their structural integrity and functional efficacy even after prolonged storage. Moreover, research indicates that incorporating marine-derived collagen into beverage formulations can significantly increase the total protein concentration while simultaneously enhancing the antioxidant activity, as evidenced by improved radical inhibition results (Farooq *et al.* 2024). Furthermore, the inclusion of these hydrolysates has been observed to influence the rheological profile of the final product, as higher concentrations typically lead to a significant increase in viscosity (León-López *et al.* 2020). However, overcoming the inherent bitterness and chemical instability of these low-molecular-weight peptides remains a significant barrier to their widespread commercialization (Ye *et al.* 2018). To address this, researchers are increasingly employing encapsulation techniques and selective enzymatic processing to mask unpleasant sensory attributes while preserving the bioactivity of the peptides (Chandran *et al.* 2023). Innovative solutions, such as the entrapment of peptides within protective biomaterials, are increasingly utilized to mitigate these sensory challenges and safeguard bioactivity against proteolytic degradation during gastrointestinal transit (Kendler *et al.* 2024). The sustainable valorization of animal by-products-including skins, bones, and cartilage-not only facilitates the production of these bioactive peptides but also addresses environmental concerns by repurposing industrial waste (Fu *et al.* 2019). Specifically, advanced enzymatic and physical extraction methods, such as ultrasound- and microwave-assisted processing, have been shown to significantly reduce production times while maximizing the yields of high-quality collagen fractions from these underutilized tissues (Waqar *et al.* 2025). Furthermore, utilizing fish scales and bone residues for collagen recovery offers a dual advantage by promoting a circular economy while providing protein-rich ingredients that exhibit significant antioxidant and antihypertensive properties (Salindeho *et al.* 2022).
Fig. 2 depicts the hierarchical structure of collagen and its enzymatic hydrolysis into low-molecular-weight bioactive peptides for functional instant beverages. The schematic shows how native collagen from bovine, porcine, and marine sources is transformed into collagen hydrolysates with improved solubility, bioavailability, and activity. The upper section illustrates collagen's multilevel organization, from fibers and fibrils to the triple-helical molecule and α-polypeptide chains.

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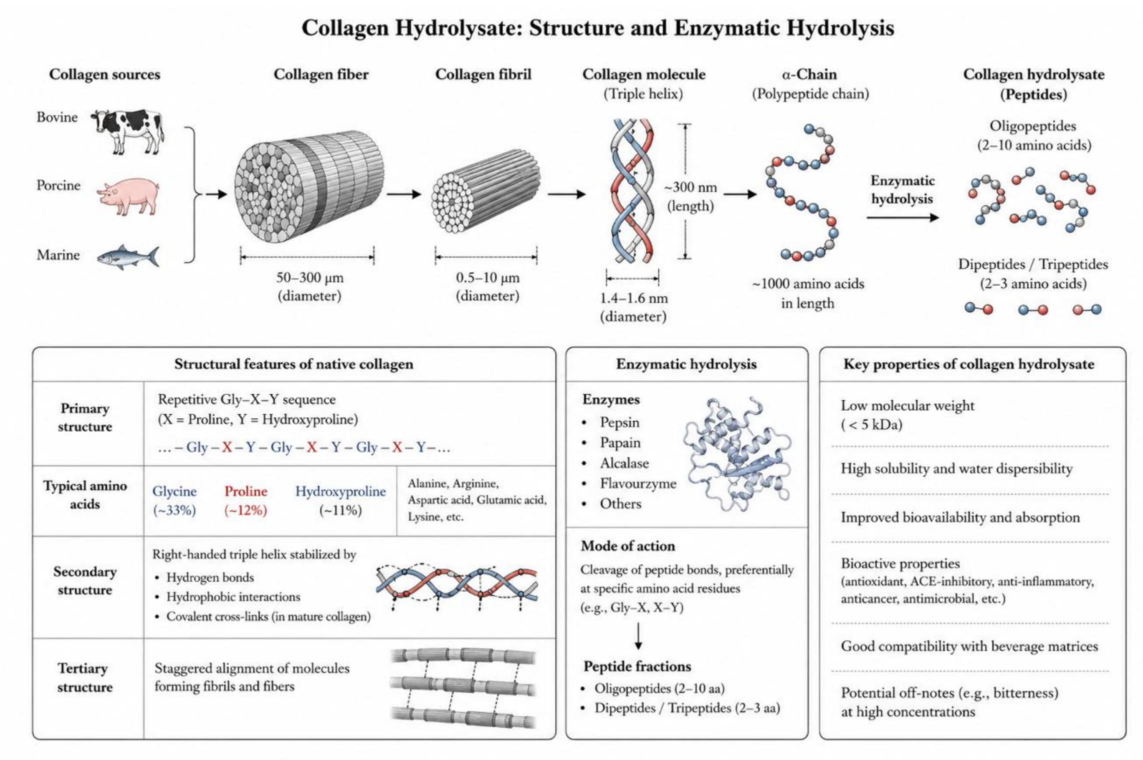

Fig2. Structural organization and enzymatic hydrolysis of collagen for functional instant beverage applications.

Native collagen has a highly ordered triple-helix structure, stabilized by hydrogen bonding, hydrophobic interactions, and intermolecular cross-linking. Its primary structure features a repetitive Gly–X–Y amino acid sequence, rich in glycine, with proline and hydroxyproline contributing to rigidity and thermal stability.

Enzymatic hydrolysis converts native collagen into smaller peptide fractions (oligopeptides, dipeptides, tripeptides) using enzymes like pepsin, papain, alcalase, and flavourzyme. This process improves water dispersibility, dissolution, and gastrointestinal absorption. Collagen hydrolysates, with their low molecular weight (<5 kDa), offer superior solubility and compatibility in beverages. They also exhibit bioactive properties such as antioxidant, ACE-inhibitory, anti-inflammatory, antimicrobial, and antihypertensive activities, making them valuable for developing health-promoting instant beverages.

Technologically, collagen hydrolysates improve emulsification and stabilize dispersed systems due to their amphiphilic nature. Controlled hydrolysis optimizes sensory characteristics and reduces aggregation during storage. However, excessive hydrolysis can lead to bitter peptides, negatively impacting taste. In essence, the process links collagen structure, enzymatic breakdown, peptide generation, and functional properties, highlighting collagen hydrolysates' utility in advanced protein-based instant beverage formulations.

As shown in Table 1, bovine, porcine, and marine collagen hydrolysates offer distinct properties for functional beverages. Marine collagen excels in solubility and antioxidant activity, while bovine collagen provides high protein and ACE-inhibitory activity. Advanced extraction methods like ultrasound and microwave processing boost peptide recovery and performance while cutting processing time. However, bitterness, thermal instability, and peptide aggregation still limit their industrial use in beverages.

3.2 Functional and biological properties

These bioactive peptides are recognized for their diverse physiological roles, including immunomodulation, antimicrobial effects, and the inhibition of enzymes such as dipeptidyl peptidase-IV and angiotensin-I converting enzyme (Nirmal *et al.* 2022).

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Table 1. Sources, functional properties, and technological characteristics of collagen hydrolysates used in functional instant beverages.

Source	Extraction method	Bioactive properties	Advantages	Limitations	References
Bovine collagen	Enzymatic hydrolysis	ACE inhibition, antioxidant activity	High protein content	Flavor instability	(Hernández-Ledesma *et al.* 2011; Nirmal *et al.* 2022; Gómez-Guillén *et al.* 2011)
Porcine collagen	Controlled proteolysis	Anti-inflammatory effects	Low production cost	Religious restrictions	(Nirmal *et al.* 2022; Toldrá *et al.* 2016)
Marine collagen	Ultrasound-assisted extraction	High antioxidant activity	Excellent solubility	Lower thermal stability	(Farooq *et al.* 2024; Waqar *et al.* 2025)
Salmon scale collagen	Microwave-assisted extraction	Radical scavenging	Improved storage stability	Bitter taste	(Farooq *et al.* 2024; Jeyachandran & Aman 2025)
Bone-derived peptides	High-pressure hydrolysis	Bone-supportive effects	Texture improvement	Aggregation	(León-López *et al.* 2020)

By mitigating the inherent bitterness associated with these hydrolysates through advanced debittering protocols, their integration into functional beverages can effectively align with broader health targets (Ying *et al.* 2021). The structural composition of these peptides, particularly the recurring Gly-Pro-Hyp sequences, is frequently associated with robust antioxidant and antihypertensive activity, facilitating their role as key functional ingredients. Furthermore, enzymatic treatments using specific proteases like alcalase or thermolysin have been shown to optimize the production of these fragments, resulting in enhanced inhibitory potency against hypertension-related biomarkers (Toldrá *et al.* 2016).

3.3 Applications in instant beverages

The integration of collagen hydrolysates into instant powder formulations requires careful consideration of particle morphology and hydration kinetics to ensure seamless reconstitution in aqueous media (Alemán Pérez & Martinez Alvarez 2013). Technological strategies such as agglomeration and the inclusion of surface-active agents are frequently employed to reduce dustiness and prevent the formation of clumps during dissolution. Beyond these physical improvements, the biological functionality of collagen in liquid matrices extends to systemic health, as peptides derived from bone and marine sources have been shown to support bone mineral density and exhibit anti-inflammatory effects (Barzkar *et al.* 2023). Moreover, these peptides possess notable metal chelating capabilities and free radical scavenging properties that contribute to the suppression of lipid peroxidation within the beverage matrix (Chen 2023). Furthermore, the inclusion of these peptides can improve the overall sensory experience by modulating the texture and viscosity of the final beverage without compromising its nutritional profile (Soutelino *et al.* 2024). Additionally, the inherent amphiphilic character of these hydrolyzed fragments, often unleashed through controlled proteolytic processes, facilitates superior emulsifying and film-forming properties that stabilize the complex matrix of instant protein drinks (Varga-Tóth *et al.* 2022). The relationship between specific peptide chain length and functional efficacy necessitates further investigation into how unique amino acid sequences influence antioxidant potential (Deng *et al.* 2023). Indeed, the bioactivity of these fragments is fundamentally dictated by their molecular weight and the specific amino acid sequences released during proteolytic hydrolysis (Ma *et al.* 2025). For instance, collagen hydrolysates have been shown to exhibit superior ACE inhibitory activities compared to other protein sources, largely due to a high concentration of proline and hydroxyproline residues that enhance antihypertensive efficacy (Cheng *et al.* 2021).

4. Combination of SPI and collagen hydrolysate

4.1 Nutritional and functional synergy

The combination of soy protein isolate and collagen hydrolysate provides a complementary amino acid profile that addresses the limitations of individual protein sources, particularly regarding essential amino acid availability and digestibility. Specifically, this binary system leverages the emulsifying and gel-forming versatility of soy protein alongside the high bioavailability of collagen-derived bioactive peptides (Ettelaie *et al.* 2017). This synergistic interaction facilitates the creation of a balanced protein matrix that enhances the overall solubility and thermal stability

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of the beverage during industrial processing (Samaei *et al.* 2020). Research indicates that the blending of these proteins can modulate the production of specific antihypertensive peptides, such as those derived from soy glycinin or collagen, thereby maximizing the overall health-promoting potential of the beverage (Coscueta *et al.* 2016). Indeed, studies combining enzymatic hydrolysis with microbial fermentation have demonstrated that such synergistic approaches can significantly amplify the angiotensin-converting enzyme inhibitory activity of these protein matrices (Daliri *et al.* 2019). Furthermore, industrial-scale processing methods such as spray-drying have been shown to optimize the secondary structure of these peptides, which can significantly enhance both their solubility and subsequent bioactivity after gastrointestinal digestion (Khongla *et al.* 2025).

4.2. Stability and Solubility

Soy protein and collagen hydrolysate synergistically improve the colloidal stability of systems, preventing protein aggregation and phase separation during industrial processing (Naik *et al.* 2022). These hydrolysates may also increase protein complex solubility by balancing hydrophobic interactions and electrostatic repulsion (Mirzaee *et al.* 2024). Specific peptide sequences form stable emulsions, crucial for maintaining the sensory quality of instant drinks (Wu & Chen 2022). Controlling the degree of hydrolysis is essential to prevent bitter hydrophobic peptides that negatively impact consumer acceptance (Sun 2011). Researchers have explored debittering techniques like exopeptidases or targeted adsorption to remove hydrophobic residues (Hu *et al.* 2022).

4.3 Sensory properties

Flavoring and structural changes to proteins help mask off-flavors in protein drinks. Encapsulation reduces the bitterness and moisture-absorbing properties of small protein fragments. Spray drying is a common industrial method for reducing hygroscopicity, improving delivery, and extending shelf life. Complexing bitter protein hydrolysates with biopolymers like maltodextrin or pectin during spray drying can delay bitterness perception until after swallowing. The smooth, non-porous microcapsules ensure controlled release, effectively masking undesirable tastes in protein-enriched foods.

5. Storage stability and quality characteristics

5.1 Hygroscopicity and shelf life

The hygroscopic nature of protein hydrolysates significantly impacts the physical stability of instant beverage powders, as high moisture uptake can lead to caking, stickiness, and accelerated degradation of bioactive compounds during storage (Gómez-Mascaraque *et al.* 2016). To mitigate these effects, the application of anti-caking agents and the selection of packaging materials with low water vapor transmission rates are essential to maintain powder flowability and shelf-life stability (Ashritha *et al.* 2024). Elevating the glass transition temperature through the use of high-molecular-weight carriers like maltodextrins effectively reduces moisture sorption and preserves the structural integrity of the encapsulated compounds (Wang *et al.* 2020). Furthermore, evaluating these functional ingredients requires rigorous monitoring of environmental parameters, as factors such as light intensity, oxygen permeability, and fluctuations in relative humidity and temperature directly dictate the bioaccessibility and degradation kinetics of bioactive peptides during shelf life (Besharati & Lackner 2023). However, despite these advancements, the bioactivity of these peptides remains susceptible to premature degradation within the human gastrointestinal tract due to enzymatic hydrolysis and rapid metabolism (Chen *et al.* 2025).

5.2. Packaging and storage conditions

The selection of barrier-optimized packaging materials is critical to minimize the permeability of oxygen and water vapor, which are primary drivers of peptide degradation and loss of functional bioactivity (Perry & McClements, 2020). Advanced encapsulation techniques, such as coaxial spray-drying and electrospraying, further complement these packaging strategies by creating shell-core architectures that physically shield sensitive bioactives from the deleterious effects of the gastrointestinal environment (Berraquero-García *et al.* 2023). By promoting sustained release and improving transport across the intestinal epithelium, these targeted delivery systems successfully mitigate the negative impacts of food processing and digestion on peptide bioactivity.

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CONCLUSION

This review systematically examines the scientific, technological, and health aspects of functional instant beverages combining soy protein isolate (SPI) and collagen hydrolysate (CH). Individually, neither protein fully meets the demands for modern high-performance beverages. However, their strategic combination creates a superior protein matrix, leveraging SPI's emulsifying and phytochemical properties with CH's bioavailable and bioactive peptides, resulting in a product with enhanced therapeutic potential and physicochemical performance.

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