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Techno-functional characterization of protein concentrate from common white beans *(Phaseolus vulgaris L.*)

Paula Zambe Azevedo
Doctor Scientiae

VIÇOSA - MINAS GERAIS
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Thesis submitted to the Food Science and Technology Graduate Program of the Universidade Federal de Viçosa in partial fulfillment of the requirements for the degree of *Doctor Scientiae*.

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Co-advisers: Evandro Martins
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Assent:

Paula Zambe Azevedo
Author

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Adviser

Dedicated to Elizete, my mother, the root of my strength and a guiding light throughout this journey, who, with steadfast hands and a generous heart, taught me to believe and never give up. Her love was the foundation upon which I built every step of this path.

And to all individuals from low-income backgrounds who make of education an act of resistance and hope. Those who, even when the ground gives way and the days grow heavy, continue forward with eyes lit by dreams and hearts sustained by courage. Knowledge does indeed open paths and offers hope. This achievement is also yours, the result of a quiet yet immense struggle for a more just, luminous future with real opportunities for all.

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As Paulo Freire stated: “No one educates anyone, no one educates themselves alone, people educate each other, mediated by the world.” May we continue to do science together, sowing questions rather than building walls. May we always be pioneers in creating paths that welcome doubt, error, and, above all, others. Sometimes with rigor, for science demands it, but never with arrogance. With that spirit, I move forward, always grateful.

“Sonho que se sonha só,
É só um sonho que se
sonha só. Mas sonho que se
sonha junto é realidade”.
(Raul Seixas)

ABSTRACT

AZEVEDO, Paula Zambe, D.Sc., Universidade Federal de Viçosa, July, 2025. **Techno-functional characterization of protein concentrate from common white beans *(Phaseolus vulgaris L.*)**. Adviser: Pedro Henrique Campelo Felix. Co-advisers: Evandro Martins and Paulo Cesar Stringheta.

This study aimed to characterize the physicochemical and technofunctional properties of the protein concentrate obtained from common white bean (Phaseolus vulgaris L.) and, thereby, to assess its potential application in the food industry. The approach also included a comprehensive review of the economic and nutritional importance of white bean, followed by the investigation of protein extraction methods, amino acid composition, structure of major proteins, application of white bean in food product development, and related challenges. Analyses revealed that white bean proteins exhibit a high content of essential amino acids, particularly lysine, leucine, and valine, as well as elevated concentrations of glutamic and aspartic acids, which may enhance functional properties such as emulsification, gel formation, and foam stability. The studies indicated that protein solubility varies according to pH and ionic strength and can be modulated by the addition of salts or the application of emerging technologies such as ohmic heating and cold plasma. Technological limitations associated with the native structure of these proteins were also discussed, including low solubility near the isoelectric point and the requirement for high concentrations to form gels. Nevertheless, the results demonstrate that, when properly extracted and processed, white bean proteins display functional properties comparable to, or even surpassing, those of commercial sources such as soy and pea proteins. It is concluded that white bean protein concentrate holds strong potential as a functional ingredient for diverse food formulations, ranging from emulsified and aerated products to plant-based meat alternatives. Furthermore, the application of emerging technologies is emphasized as a promising strategy to enhance protein functionality and broaden its applicability across different food matrices.

Keywords: plant-based; vegetable protein concentrate ; alternative proteins; emerging technologies; technofunctional properties

RESUMO

AZEVEDO, Paula Zambe, D.Sc., Universidade Federal de Viçosa, julho de 2025. **Caracterização tecno-funcional do concentrado proteico do feijão branco comum (P*haseolus vulgaris L.*)**. Orientador: Pedro Henrique Campelo Felix. Coorientadores: Evandro Martins e Paulo Cesar Stringheta.

Este trabalho teve como objetivo caracterizar as propriedades físico-químicas e tecno-funcionais do concentrado proteico obtido do feijão comum branco (Phaseolus vulgaris L.), e através disso observar seu potencial para aplicação na indústria de alimentos. A abordagem também contemplou uma revisão ampla sobre a importância econômica e nutricional do feijão branco, seguida da investigação dos métodos de extração proteica, composição de aminoácidos, estrutura das proteínas majoritárias, aplicação do feijão branco no desenvolvimento de produtos alimentícios e os desafios a serem considerados. As análises revelaram que as proteínas do feijão branco apresentam elevado teor de aminoácidos essenciais, com destaque para lisina, leucina e valina, além de alta concentração de ácidos glutâmico e aspártico, o que pode favorecer propriedades como emulsificação, formação de gel e estabilidade de espuma. Os estudos indicaram que a solubilidade das proteínas varia conforme o pH e a força iônica, sendo possível modulá-la por meio da adição de sais ou aplicação de tecnologias emergentes como aquecimento ôhmico e plasma frio. Foram também discutidas limitações tecnológicas associadas às proteínas em sua forma nativa, como baixa solubilidade em pH próximo ao ponto isoelétrico e necessidade de altas concentrações para formação de géis. No entanto, os resultados demonstram que, quando extraídas e processadas adequadamente, essas proteínas exibem propriedades funcionais comparáveis, ou superiores, às de fontes comerciais, como soja e ervilha. Conclui-se que o concentrado proteico de feijão branco pode possuir alto potencial como ingrediente funcional para formulações alimentícias diversas, desde produtos emulsificados e aerados até alternativas vegetais à carne. Ainda, ressalta-se a importância da aplicação de tecnologias emergentes para aprimorar sua funcionalidade e ampliar sua aplicabilidade em diferentes matrizes alimentícias.

Palavras-chave: plant-based; concentrado proteico vegetal; proteínas alternativas; tecnologias emergentes; propriedades tecnofuncionais

SUMMARY

1 GENERAL INTRODUCTION

The growing demand for sustainable foods aligned with plant-based diets has driven the search for alternative protein sources that combine technological feasibility, nutritional quality, and low environmental impact (Affrifah; Uebersax; Amin, 2023; Yanni et al., 2023). In this context, legumes have emerged as promising candidates, not only due to their high protein content, but also because of their fiber and bioactive compound content, their contribution to sustainable agricultural systems, and their excellent processing properties (Affrifah; Uebersax; Amin, 2023; Náthia-Neves et al., 2025; Zhang et al., 2024).

Among these, white bean (*Phaseolus vulgaris* L.) has gained research interest due to its functional composition and the technological potential of its proteins, which include high emulsifying capacity, stable foam formation, and good oil absorption (Azevedo et al., 2025), making them suitable for food industry applications. Despite these promising characteristics, comprehensive studies on white bean proteins remain scarce when compared to well-established plant sources such as soy and pea (Fischer; Cachon; Cayot, 2020; Lu et al., 2020; Zhang et al., 2024).

White beans are widely consumed in Western countries and include various light-colored cultivars, such as common white beans and navy beans. Although these belong to the same species as other common beans, they exhibit subtle differences in flavor, texture, and size (Jafari et al., 2016; Park; Rupert; Yu, 2007). Despite their established presence in the human diet, white bean production in Brazil remains limited and insufficient to meet domestic demand, leading to regular imports (CNA, 2022). Internationally, however, white beans are gaining relevance, with Canada standing out as the world's leading producer and exporter (Li et al., 2017; Sikkema et al., 2008; Val, 2022).

Proteins extracted from white beans exhibit a favorable amino acid profile, with significant levels of lysine, leucine, arginine, tyrosine, and phenylalanine, and are naturally gluten-free, making them a viable option for developing products targeted at consumers with dietary restrictions (Sahasrabudhe et al., 1981). Although plant proteins such as soy are widely used in the food industry due to their availability, functionality, and high protein content, efforts have intensified to explore alternative sources (Costa et al., 2025; Liu; Pei; Heinonen, 2022; Nazir; Wani, 2023; Tarahi; Abdolalizadeh; Hedayati, 2024; Zhao et al., 2020), considering concerns related to allergenicity, the presence of antinutritional factors, and the environmental impact of soy cultivation (Zhang et al., 2024).

Although white bean proteins demonstrate promising technological potential, they remain underexplored compared to commercially established plant protein sources. Therefore, understanding and characterizing their physicochemical and functional properties is essential to expanding their use as an alternative ingredient in plant-based food formulations.

Accordingly, the objective of this study was to investigate the technofunctional characteristics of white bean protein concentrate (*Phaseolus vulgaris* L.) and compare them with widely used commercial proteins such as soy protein isolate and pea protein concentrate. The aim is to expand scientific knowledge on this legume and provide evidence-based support for the development of food products with technologically modulated ingredients, contributing to the diversification of plant-based protein sources and the promotion of more sustainable production chains.

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ARTICLE 1

White bean (*Phaseolus vulgaris* L.) proteins: extraction methods, physicochemical and techno-functional properties, applications, and challenges for the food industry

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RESUMO
Este artigo destaca o potencial do feijão branco como uma fonte nutritiva e sustentável, especialmente no contexto do consumo de produtos à base de plantas. O objetivo desta revisão foi aprofundar o entendimento sobre as proteínas do feijão branco, abordando sua composição, estrutura, propriedades e as possibilidades de sua aplicação no desenvolvimento de novos

alimentos. O feijão branco apresenta composição nutricional relevante em relação ao teor de proteínas, ao amido com elevado teor de amilose e fibras que contribuem para o baixo índice glicêmico, além de minerais essenciais. As proteínas do feijão branco são ricas em aminoácidos essenciais, como lisina, leucina e valina, além de apresentarem altos teores de ácido glutâmico e aspártico que contribuem positivamente na formação e estabilização de géis, espumas e emulsões. O elevado teor de globulinas também contribui para a elevada atividade emulsificante dessas proteínas. Suas capacidades de retenção de óleo e água são superiores às de proteínas comerciais, como a de soja e ervilha, apresentando afinidade por moléculas polares, sendo indicadas para maioneses, molhos e embutidos. No entanto, as proteínas do feijão branco apresentam algumas limitações tecnológicas, que podem ser mitigadas com o uso de tecnologias emergentes. Os achados deste artigo sobre as propriedades e o perfil nutritivo desta leguminosa podem deixá-la em evidência, aumentando seu consumo e uso como ingrediente alimentar, aliado ao aumento de investigações que melhorem suas limitações.

Palavras-chave: Leguminosas, Globulinas, Fatores antinutricionais, *Plant based*, Tecnologias emergentes.

ABSTRACT

This article highlights the potential of white beans (*Phaseolus vulgaris* L.) as a nutritious and sustainable protein source, particularly within the growing demand for plant-based products. This review aimed to deepen the understanding of white bean proteins by discussing their composition, structure, properties, and potential applications in the development of novel food products. White beans exhibit a relevant nutritional profile, with high protein content, starch rich in amylose, and significant fiber levels, contributing to a low glycemic index, along with essential minerals. White bean proteins are rich in essential amino acids such as lysine, leucine, and valine, and contain high levels of glutamic and aspartic acids, which play a key role in the formation and stabilization of gels, foams, and emulsions. The high globulin content further enhances the emulsifying activity of these proteins. Additionally, their water- and oil-holding capacities surpass those of commercial proteins like soy and pea, demonstrating strong affinity for polar molecules, making them suitable for products such as mayonnaise, sauces, and meat analogues. However, some technological limitations are associated with native white bean proteins, which may be mitigated through the application of emerging technologies. The findings presented in this review regarding the nutritional profile and functional properties of white bean proteins may contribute to increasing their utilization in the food industry, while also encouraging further research to overcome their current limitations.

Keywords: Legumes, Globulins, Antinutritional factors, Plant-based, Emerging technologies.

RESUMEN

Este artículo destaca el potencial del frijol blanco como una fuente nutritiva y sostenible, especialmente en el contexto del consumo de productos de origen vegetal. El objetivo de esta revisión fue profundizar en la comprensión de las proteínas del frijol blanco, abordando su composición, estructura, propiedades y las posibilidades de su aplicación en el desarrollo de nuevos alimentos. El frijol blanco presenta una composición nutricional relevante en cuanto al contenido proteico, al almidón con alto contenido de amilosa y fibras que contribuyen a un bajo índice glucémico, además de minerales esenciales. Las proteínas del frijol blanco son ricas en aminoácidos esenciales, como lisina, leucina y valina, además de presentar altos niveles de ácido glutámico y aspártico, los cuales contribuyen positivamente a la formación y estabilización de geles, espumas y emulsiones. El elevado contenido de globulinas también contribuye a la alta actividad emulsionante de estas proteínas. Su capacidad para retener aceite

y agua es superior a la de proteínas comerciales, como las de soja y guisante, presentando afinidad por moléculas polares, siendo indicadas para mayonesas, salsas y embutidos. Sin embargo, las proteínas del frijol blanco presentan algunas limitaciones tecnológicas, que pueden mitigarse mediante el uso de tecnologías emergentes. Los hallazgos de este artículo sobre las propiedades y el perfil nutricional de esta leguminosa pueden posicionarla favorablemente, aumentando su consumo y uso como ingrediente alimentario, junto con un incremento en las investigaciones que mejoren sus limitaciones.

Palabras clave: Leguminosas, Globulinas, Factores antinutricionales, Productos de origen vegetal, Tecnologías emergentes.

1 INTRODUCTION

The growing demand for more sustainable, nutritionally balanced foods aligned with plant-based diets has driven the search for alternative protein sources. In this context, legumes stand out not only for their nutritional profile, rich in proteins, fiber, complex carbohydrates, and bioactive compounds, but also for their contribution to sustainable agricultural practices, such as biological nitrogen fixation and the reduction of chemical fertilizer use (Kamakaula, 2024; Uebersax et al., 2023; Qin, Wang; Luo, 2022).

White bean (*Phaseolus vulgaris* L.) is one of the most widely consumed legumes, especially in Western countries, where it plays a significant role in the diet. This group includes various light-colored cultivars, such as common white bean, white mottled bean, Cannellini, and Navy bean, which, although belonging to the same species as common beans, exhibit subtle differences in flavor, texture, and size (Park; Rupert; Yu, 2007). These varieties have attracted growing interest from the scientific community not only because of their nutritional profile but also due to promising technological properties that may favor their application in the food industry (Khan et al., 2025; Azevedo et al., 2025; Tabtabaei et al., 2019; Kereliuk; Kozub, 1995).

From an economic perspective, white bean has shown increasing relevance in the global legume market, with Canada standing out as the world's largest producer, accounting for approximately 42% of global production, in addition to being one of the main exporting countries of this crop (Sikkema et al., 2008; Li et al., 2017; Shibles et al., 2022). In the Brazilian context, although total bean production reached approximately 2.84 million tons in 2022, the share of white bean remains limited and insufficient to meet domestic demand. As a result, Brazil needs to import between 10,000 and 15,000 tons annually, mainly from Argentina, to supply the domestic market (CNA, 2022).

White bean exhibits a functional composition comprising proteins, carbohydrates, soluble fibers, vitamins, and various bioactive compounds, which contribute both to its nutritional value and potential health benefits (García-Lafuente et al., 2014; Sahasrabudhe et al., 1981). Among these compounds, proteins have gained prominence, particularly regarding their technological properties (Azevedo et al., 2025; Khan et al., 2025; Ramos et al., 2024; Gundogan; Karaca, 2020; Jafari et al., 2016).

The performance of plant proteins derived from white bean in food systems is intrinsically linked to their physicochemical and technofunctional properties, which influence essential parameters such as solubility, emulsifying capacity, foam formation and stability, water and oil retention, as well as gelation ability. These properties are critical not only to ensure product stability, texture, and sensory quality but also to enable their incorporation into a wide range of applications within the food industry, including meat analogues, bakery products, emulsions, aerated systems, and protein supplements.

However, despite their nutritional and technological potential, white bean proteins remain underexplored compared to those from other well-established plant sources such as soy and pea (Choudhury et al., 2025; Shanthakumar et al., 2022; Qin; Wang; Luo, 2022; Bildstein et al., 2008). This scenario underscores the need for increased research investment to deepen the physicochemical characterization, functional properties, and applicability of these proteins, aiming to expand their use in the development of innovative and sustainable food products.

Thus, this review aims to compile and analyze the available scientific literature on white bean, comprehensively addressing the following aspects: its economic importance, with emphasis on production and market trends; its nutritional composition; the physicochemical and technofunctional properties of its proteins; the applications of white bean protein in the food industry; and the main challenges related to its use in food products. It is expected that the information gathered in this work will support future research and foster the development of new products and strategies that promote the use of white bean and its protein concentrates and isolates, enhancing the value of this legume from nutritional, technological, and socioeconomic perspectives.

2 MATERIALS AND METHODS

A meta-analysis technique was conducted in several steps, including literature search, study selection, data extraction, and eligibility assessment (Faridah et al., 2022; Matos et al., 2024). The inclusion criteria comprised studies addressing beans of the species *Phaseolus*

vulgaris L., with particular emphasis on the white bean variety, while studies involving other legumes were excluded.

3 ECONOMIC MARKET AND CONSUMPTION TRENDS

In the search for a new generation of processed foods that are affordable, palatable, desirable, healthy, and sustainable, the food industry recognizes legumes as playing a key role as an excellent source of protein in the human diet (Pérez et al., 2024). In this context, white beans represent one of the main legumes consumed globally, standing out for their economic importance and nutritional value within the agricultural production chain. The growing global production of legumes, including white beans, reflects their increasing demand, driven by their health benefits and versatility in various culinary applications (Maphosa; Jideani, 2017).

North America is the largest producer of white beans worldwide, with Canada accounting for approximately 42% of this production (Sikkema et al., 2008). Production is mainly concentrated in the provinces of Ontario and Manitoba (Li et al., 2017).. Furthermore, Canada stands out as a major exporter of this legume, contributing significantly to the global market (Val, 2022).

In the national context, Brazil produced 2,842,395 tonnes of beans in 2022, corresponding to R$ 12,374,460.00, with Minas Gerais being one of the main producing states and exhibiting the highest productivity levels (Embrapa, 2023; IBGE, 2022). However, according to the Brazilian Confederation of Agriculture and Livestock (CNA), the production of white beans in Brazil is very low, leading the country to import between 10,000 and 15,000 tonnes of white beans annually. In 2019, imports reached nearly 12,000 tonnes, with Argentina being the main supplier of this product to Brazil (CNA, 2022). Due to the low domestic production, there are no precise estimates for white bean production in Brazil, as the National Supply Company (CONAB) reports estimates based only on the scientific nomenclature (*Phaseolus vulgaris* L.), which encompasses several bean varieties, including white beans.

White beans are known for offering several health benefits, primarily due to their nutritional composition and bioactive compounds. These benefits include weight management support, improved iron bioavailability, and promotion of liver health (Feng et al., 2023; Jäger et al., 2024; Tako & Glahn, 2010). The consumption of white beans can be particularly advantageous for individuals seeking weight control and overall health improvement.

In this regard, consumption trends for this legume include a growing preference for healthy and functional foods, increased demand for plant-based products, and greater consumer

awareness regarding environmental sustainability. This trend is driven by the need for food systems that balance human health with ecological integrity, fostering growing interest in legumes such as white beans.

Consumers are increasingly seeking healthier food choices, and white beans provide bioactive compounds and dietary fiber associated with improved glycemic and lipid profiles. Moreover, they offer high protein content, which enhances the sensory properties and acceptance of gluten-free products (Tuna et al., 2023).

Therefore, the consumption of healthy products must be aligned with sustainable production practices that preserve ecological integrity. The cultivation of white beans promotes sustainable agricultural practices, including nitrogen fixation, which reduces the need for chemical fertilizers (Uebersax et al., 2023). Additionally, their short growth cycle and low carbon footprint contribute to crop diversification, improving soil health and resilience to climate variability (Uebersax et al., 2023). These sustainable agricultural practices are aligned with the United Nations Sustainable Development Goals (SDGs), addressing issues such as food security and responsible consumption (Kamakaula, 2024).

On the other hand, although the trend toward sustainable agriculture and increased white bean consumption is promising, challenges such as market access, consumer awareness, and the need for political support remain significant barriers to the broader adoption of this bean variety.

In the context of plant-based food production, Latin America holds intermediate positions in the global market: third place in the plant-based cheese segment, fourth in plant-based meats and milks, and fifth in plant-based yogurts. Nevertheless, investments from Latin American companies in this sector remain significantly lower than those observed in North America and Europe (Good Food Institute, 2023). In this scenario, the development of research focused on the characterization and utilization of plant proteins becomes essential, considering their technological and nutritional potential. These proteins emerge as promising alternatives due to their economic feasibility and lower environmental impact compared to animal-derived proteins (Henchion et al., 2017; Saldanha Do Carmo et al., 2023).

4 NUTRITIONAL COMPOSITION

White beans (Figure 1) are recognized for their high nutritional value, making them an excellent food source. They are primarily composed of proteins, carbohydrates, dietary fiber, and minerals. Their nutritional composition varies depending on factors such as variety,

processing methods, and cultivation conditions; however, in general, they present a highly nutritious profile.

Figure 1. Proximate composition of white bean (*Phaseolus vulgaris* L.)

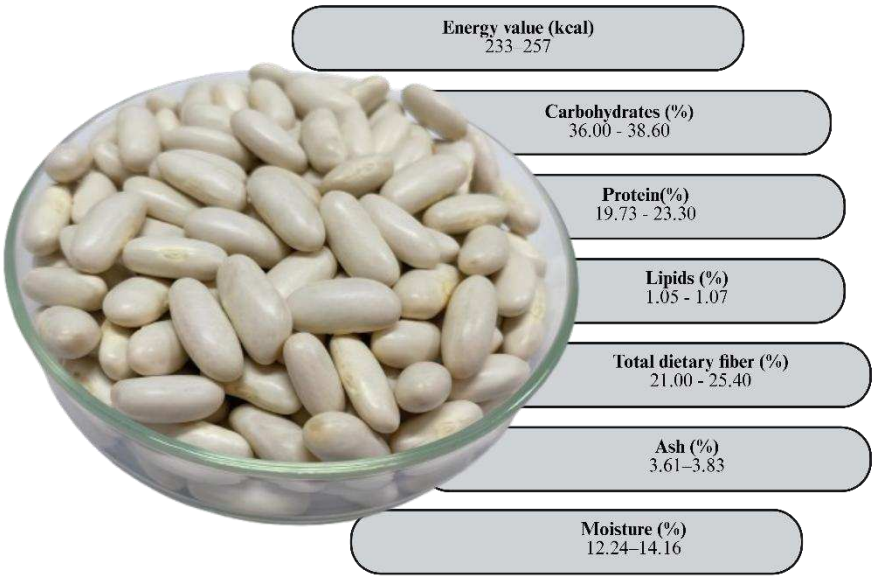


Image illustrating white bean seeds, a legume widely used in the food industry, recognized for its high protein content and technological versatility.
Source: Authors' own elaboration (2025).

As previously mentioned, white beans are characterized by their high protein content, which exhibits excellent techno-functional properties for use as a food ingredient, particularly in plant-based products (Azevedo et al., 2025). Studies conducted by El-Syiad & Hassan (2014) reported protein contents ranging from 22.55 to 64.19 g.100 g^{-1} dry weight, depending on the variety and processing methods such as soaking, conventional cooking, soaking followed by cooking, and microwave cooking (El-Syiad; Hassan, 2014). Similarly, Kereliuk and Kozub (1995) reported an average protein content of 253 $g.kg^{-1}$ dry weight in white beans cultivated in three different regions of Canada. When evaluating the nutritional composition of flours obtained from two different white bean cultivars, they found protein contents of 19.73% and 23.3%, respectively. Another study reported protein contents ranging from 19% to 27%, composed of approximately 37% albumins, 35% globulins, and less than 1% glutelins and prolamins (Hall; Hillen; Garden-Robinson, 2017).

In addition to being an excellent source of plant-based protein, white beans are rich in

carbohydrates, which serve as an important energy source. Among these carbohydrates, starch is the predominant component, typically containing about 30% amylose, an important molecule in the food industry due to its application as a binder, thickener, and stabilizer (Sahasrabudhe et al., 1981; Du et al., 2014). Studies by Kumari and Sit (2024) and Maaran et al. (2014) reported amylose contents of 27.18% and 26.5%, respectively.

White beans contain approximately 67–75% carbohydrates, including 6–8% sugars, 21–40% starch, and 14–25% dietary fiber (Kumari and Sit, 2024; Hall, Hillen, and Garden-Robinson, 2017). Notably, the high fiber content contributes to digestive health, assists in regulating intestinal transit, and helps control blood sugar levels, making white beans a valuable source of this nutrient.

The pasting properties of starch are key physicochemical characteristics that influence its behavior during heating, gel formation, and retrogradation upon cooling (Balet et al., 2019). White bean starch exhibits a pasting temperature of approximately 78 °C, which is lower than corn starch but higher than potato starch (Du et al., 2014). Hoover and Ratnayake (2002) reported pasting temperatures ranging from 70 to 72 °C for two white bean varieties. Additionally, white bean starch demonstrates higher final viscosity and setback viscosity compared to conventional starches (Du et al., 2014), indicating its potential to improve food texture. In fact, legume starches tend to form more viscous pastes and exhibit greater resistance to granule rupture under shear stress compared to cereal starches (Punia et al., 2020). This shear resistance, attributed to strong interactions among starch components within the granule, allows white bean starch to function effectively as a thickening agent in aqueous food systems (Punia et al., 2020).

Certain technological properties are essential for determining starch applications. According to Kumari and Sit (2024), white bean starch exhibits a water absorption capacity of 97.39%, oil absorption capacity of 158.39%, and solubility of 9.44%.

Regarding digestibility, white bean starch contains resistant starch levels of 77.4% in raw starch and 10.2% in cooked starch (Du et al., 2014). High levels of resistant starch are desirable in both research and the food industry due to their associated health benefits, including glycemic control and improved gut microbiota (Lockyer; Nugent, 2017).

Lipids are the least abundant macronutrient in white beans, accounting for approximately 2% of their composition. The primary fatty acids present are palmitic (18%), stearic (4%), oleic (14%), linoleic (25%), and linolenic acids (40%) (Caprioli et al., 2016). The predominance of unsaturated fatty acids contributes to cardiovascular health benefits.

Furthermore, white beans are rich in essential minerals such as potassium, magnesium,

calcium, iron, and manganese (El-Syiad; Hassan, 2014; Kereliuk; Kozub, 1995). The ash content ranges from 4.0% to 4.9%, including 138–330 mg/100 g of calcium, 4.2–7.8 mg/100 g of iron, 170–208 mg/100 g of magnesium, 1335–1946 mg/100 g of potassium, 398–621 mg/100 g of phosphorus, and 2.1–3.0 mg/100 g of zinc (Hall; Hillen; Garden-Robinson, 2017).

In summary, the nutritional composition of white beans makes them a highly nutritious food, contributing to a balanced and healthy diet. Their richness in protein with excellent techno-functional properties, alongside starch, dietary fiber, and essential minerals, underscores their relevance in promoting health, preventing disease, and serving as a promising alternative ingredient in the food industry.

4.1 ANTINUTRITIONAL FACTORS

Considering its high nutritional value, white bean (*Phaseolus vulgaris* L.) is a legume widely consumed, particularly as a source of plant-based proteins, fibers, vitamins, and minerals. However, like other legumes, it contains compounds known as antinutritional factors (ANFs), such as phytates, tannins, oxalates, lectins, enzyme inhibitors (e.g., trypsin inhibitor, amylase inhibitor), and saponins, which can interfere with the absorption of various macronutrients and micronutrients. Consequently, these compounds reduce the nutritional value and protein digestibility of foods (Rahate; Madhumita; Prabhakar, 2021; Sánchez-Quezada et al., 2024).

Several processing techniques have been employed to reduce or eliminate the adverse effects caused by ANFs present in legumes such as white beans (Table 1) (Al-Numair et al., 2009; El-Maki et al., 2007; Linsberger-Martin et al., 2013; Poblete et al., 2020). Among the physical methods, milling followed by dehulling stands out, while practices such as soaking, germination, and cooking are commonly used to mitigate the presence of these compounds. Additionally, chemical methods are also applied, based on the use of agents capable of forming complexes with ANFs, contributing to their inactivation.

These technological approaches not only enhance the bioavailability of nutrients by reducing the activity of ANFs but also improve sensory characteristics such as taste and palatability. The appropriate selection of processing techniques requires an in-depth understanding of the chemical nature of ANFs, their distribution within the seed compartments, biological effects, thermal stability, and water solubility. Among the most widely employed methods for reducing or eliminating these compounds are heating, extrusion cooking, milling, dehulling, soaking, germination, fermentation, and conventional cooking (Kumar et al., 2022).

Table 1 – Techniques for Minimizing Antinutritional Factors in Legumes

Technique	Effect
Irradiation	Can inactivate trypsin inhibitors in pulses due to the disruption of sulfhydryl (–SH) and disulfide (–S–S–) bonds.
Germination	Reduces the content of phytic acid, enzyme inhibitors, and lectins.
Cooking	Effective in reducing trypsin inhibitors, hemagglutinin activity, tannins, saponins, raffinose, stachyose, and verbascose.
Soaking	Reduces levels of phytates, tannins, and, to a lesser extent, cyanogenic glycosides.
Dehulling	Reduces tannins, saponins, and total phenolics but may increase the levels of phytic acid, trypsin inhibitor, chymotrypsin inhibitor, and α-amylase inhibitor. This may be attributed to the higher concentration of these ANFs in the cotyledon compared to the seed coat.

This table presents different processing methods used to reduce antinutritional compounds present in legumes such as beans, highlighting their effects on these factors.
Source: Adapted from Kumar et al. (2022).

Poblete et al. (2020) investigated the effects of germination and thermal processing on the activity of antinutritional factors in white bean (*Phaseolus vulgaris* L.) seeds, comparing them to raw seeds. The authors observed that germination significantly reduced hemagglutinating activity (lectins), with values of 3.06 $HU.mg^{-1}$ compared to 6.20 $HU.mg^{-1}$ in raw seeds. After cooking, no lectin activity was detected in the analyzed seeds, indicating complete inactivation. Thermal treatments, either boiling in water or autoclaving, proved highly effective in eliminating these toxic proteins. According to Kumar et al. (2022), heating the seeds at 100 °C for 10 minutes is sufficient to inactivate hemagglutinating activity. Furthermore, pressure cooking at 121 °C for 10 minutes resulted in an approximate 50% reduction in phytic acid content (from 1.23 $mg.100\ g^{-1}$ to approximately 0.61 $mg.100\ g^{-1}$) and a 45% reduction in tannins (from 980 $mg.100\ g^{-1}$ to around 539 $mg.100\ g^{-1}$), as reported by Rehman and Shah (2005).

In another study, ElMaki et al. (2007) evaluated the effects of soaking alone and the combination of soaking followed by cooking on the levels of phytates and polyphenols in white beans. The authors reported that soaking, regardless of the duration, significantly reduced these compounds compared to untreated seeds. Longer soaking times led to more pronounced reductions in phytic acid content. Additionally, the combination of soaking followed by cooking resulted in slightly higher reductions in phytate levels compared to direct cooking of raw seeds. Polyphenols exhibited a similar behavior, with progressive reductions after soaking and the combined processing. The reduction in phytate levels during soaking is mainly attributed to the leaching of phytate ions into the soaking medium, driven by a concentration gradient that regulates the diffusion rate of these compounds.

Linsberger-Martin et al. (2013) assessed the effects of high hydrostatic pressure (600 MPa, 60 °C, for 60 minutes) on the composition of antinutritional factors and protein

digestibility in white beans. The authors reported a reduction of up to 48% in oligosaccharides, non-digestible carbohydrates associated with intestinal gas production, although this reduction was lower than that achieved by conventional thermal cooking, which reached approximately 80%. Phytic acid content was reduced by up to 11% following high-pressure treatment. In contrast, total phenolic acids were only slightly affected, whereas conventional cooking resulted in substantially greater reductions, up to 78%. Trypsin inhibitor activity was considerably reduced, up to 84%, after high-pressure processing, which positively impacted protein bioavailability. Consequently, white beans subjected to this treatment exhibited an 8.7% increase in protein digestibility.

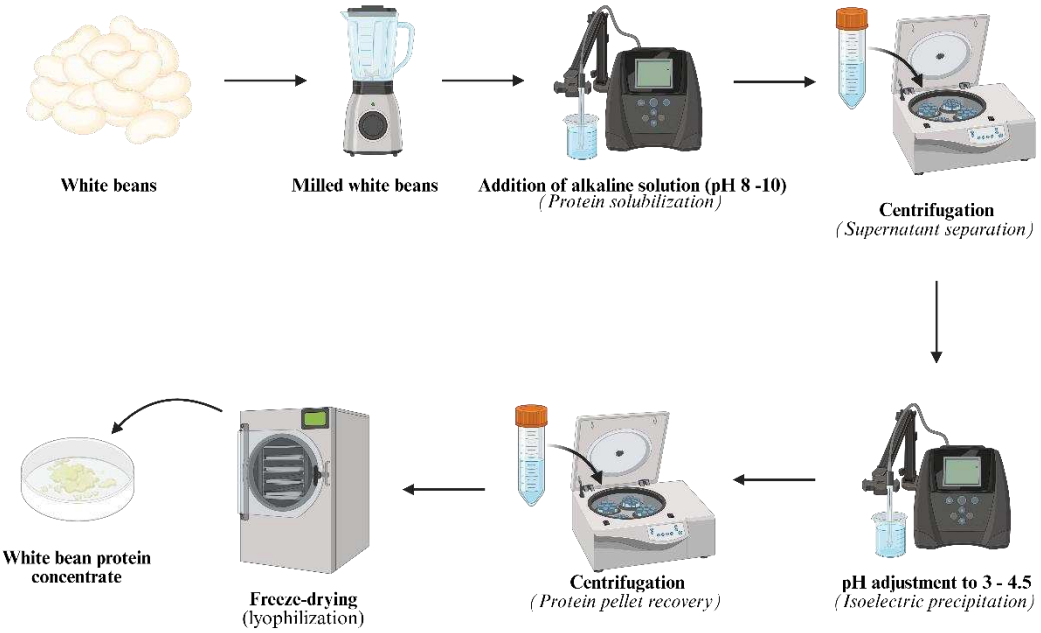
Therefore, the identification and mitigation of antinutritional factors in white beans are essential to ensure their safe and effective incorporation into a balanced diet. Moreover, the application of appropriate processing methods not only minimizes the risks associated with these compounds but also preserves or even enhances the nutritional and functional properties of this legume, expanding its potential for use in the development of healthier and technologically viable food products.

5 WHITE BEAN PROTEINS

5.1 METHODS FOR WHITE BEAN PROTEIN EXTRACTION

Protein extraction from white bean (*Phaseolus vulgaris* L.) has gained increasing attention due to the growing interest in plant-based protein sources, particularly in nutritional and functional contexts (Azevedo et al., 2025; Jafari et al., 2016; Khan et al., 2025; Ramos et al., 2024). Various methodologies have been studied and applied to optimize both yield and quality of extracted proteins, considering factors such as solubility, structural integrity, and suitability for food applications. Among the most commonly employed methods for white bean protein extraction are alkaline extraction followed by isoelectric precipitation (Figure 2) (Azevedo et al., 2025; Khan et al., 2025). Additionally, saline solutions and more advanced techniques such as ultrasound-assisted extraction and high-pressure extraction (Chandran; Suri; Choudhary, 2023; Khan et al., 2025; Náthia-Neves et al., 2025) have been employed for legume protein isolation.

Figure 2. Flowchart of the extraction process of the protein fraction from white bean (*Phaseolus vulgaris* L.) using the alkaline extraction followed by isoelectric precipitation method.



White bean seeds are ground in an aqueous medium, with pH adjustment to alkaline conditions to promote protein solubilization. The suspension is then centrifuged to remove the insoluble residues, and the supernatant pH is adjusted to the isoelectric point of the proteins to induce their precipitation. A second centrifugation is performed to collect the protein pellet, which is subsequently freeze-dried to obtain the protein concentrate in powder form.
Source: Authors' own elaboration (2025).

Khan et al. (2025), investigating ultrasound-assisted extraction of proteins from white bean flour using a frequency of 20 kHz, demonstrated that ultrasound exposure time is a critical parameter for process efficiency. The study showed that prolonged exposure (e.g., 20 minutes) can compromise protein purity, likely due to structural degradation, co-extraction of impurities, and increased susceptibility to oxidation. These effects suggest loss of functional protein integrity, underscoring the need to optimize treatment duration. Conversely, shorter exposure times (≤15 minutes) were more effective compared to conventional extraction methods. Under these conditions, extraction efficiency improved alongside enhancements in protein functional properties, including increased solubility, improved emulsifying capacity, and enhanced foaming ability. Moreover, these structural modifications favored applications in products requiring specific textural attributes, such as plant-based meat analogs. Notably, the minimum gelation concentration decreased from 18% in the control sample to 12% after 10 minutes of ultrasound treatment.

Tabtabaei et al. (2019) explored a sustainable, chemical-free strategy for fractionating white bean flour via dry triboelectric separation. This process enabled the recovery of protein

fractions with higher albumin content compared to conventionally produced protein isolates from wet fractionation methods. The obtained fractions exhibited high nitrogen solubility index at their intrinsic pH, as well as notable emulsifying and foaming properties. Conversely, protein isolates derived from wet fractionation were significantly depleted in albumins, displaying low solubility and foaming capacity, although they showed high water and oil absorption capacities. Therefore, dry triboelectric separation proved a promising alternative to traditional wet extraction methods, yielding protein concentrates with enhanced functional properties suitable for food applications.

Extraction methods vary considerably in their operating principles, efficiency, impact on protein functional quality, type of protein matrix, and economic feasibility. Consequently, method selection depends on variables such as the intended end-use of the protein, operational costs, and effects on the functional properties of the protein extract.

Table 2 provides a comparative overview of different methods used for plant protein extraction. It presents the underlying principles guiding each technique, as well as their main advantages and limitations. This comparison enables a critical evaluation of available options, considering their feasibility for both laboratory scale and potential industrial applications.

Table 2 – Comparative summary of potential methods for plant protein extraction

Extraction Method	Principle/Characteristic	Advantages	Disadvantages
Alkaline + Isoelectric Precipitation	This is the most commonly used technique. It involves solubilizing proteins in an alkaline solution (pH 8–10) followed by isoelectric precipitation.	High extraction efficiency, particularly for globulins. It is a low-cost method and scalable at the industrial level.	Risk of protein denaturation, formation of undesirable compounds such as lysinoalanine, and generation of alkaline waste.
Salt + Dialysis	This method uses saline solutions at neutral pH to solubilize proteins at moderate temperatures (up to 35 °C), followed by recovery steps through membrane processes (dialysis) or precipitation at low temperatures (1–4 °C).	Better preservation of functional protein properties due to milder processing conditions.	Slower process with challenges for industrial scalability, and high water consumption.
Enzymatic Extraction	Uses enzymes (carbohydrases/proteases) to break down the cell wall and release proteins from the material.	Produces high-quality proteins with minimal degradation; can also reduce antinutritional factors.	High cost of enzymes, requires precise process control, and tends to be time-consuming.
Microwave-Assisted Extraction	Uses non-ionizing electromagnetic radiation (300 MHz to 300 GHz) to	Fast process, uniform heat distribution, low	Risk of thermal degradation of heat-sensitive

	rapidly heat the material via dipole rotation and ionic conduction, breaking hydrogen bonds in the cell walls to facilitate protein extraction.	solvent usage, and good energy efficiency.	compounds and requires specific equipment.
Ultrasound-Assisted Extraction	Applies ultrasonic waves (20 to 1000 kHz) that generate cavitation, rupturing cells and releasing proteins.	Rapid method with low solvent use. Increases extraction yield (by ~20%) and improves protein solubility. Can reduce the allergenic potential of plant proteins.	Requires specialized equipment. May not be efficient for certain protein types and can cause denaturation, affecting functional properties (RE and RFE).
Pulsed Electric Field (PEF)	Applies short electrical pulses (10–80 $kV.cm^{-1}$) to create temporary pores in cell membranes, enhancing protein release.	As a non-thermal process, it helps preserve protein functional properties and is effective even at larger volumes.	Requires specialized equipment, may have limited effectiveness depending on the type of plant cells, and its efficiency depends on the conductivity of the treated medium.
Ohmic Heating	Involves the passage of electrical current through the material. The natural electrical resistance of the food generates internal and uniform heating (Joule effect), facilitating protein extraction.	Provides rapid and uniform heating, requires less water and solvents, minimizes waste, achieves higher extraction yields, superior extract quality, and shorter processing times. Also minimizes thermal degradation.	Challenges include handling viscosity, electrical conductivity, and fouling deposits. Requires precise control of current, voltage, and temperature to avoid protein denaturation and compound degradation. May not be effective for certain food matrices.

RE = Reduced Emulsification; RFE = Reduced Foaming Ability.
The table provides a comparative overview of different plant protein extraction methods, organized into four columns: extraction method, main principle/characteristic, key advantages, and main disadvantages associated with each technique.
Source: Adapted from Chandran, Suri, and Choudhary (2023); and Náthia-Neves et al. (2025).

The diversity of protein extraction methods highlights significant potential to optimize both yield and protein quality, meeting the specific demands of the food industry. While

conventional methods, such as alkaline extraction followed by isoelectric precipitation, offer good efficiency at relatively low costs, more advanced techniques, including ultrasound- and microwave-assisted extraction, are gaining prominence for enhancing protein functional properties, such as improved solubility, emulsifying capacity, and foaming ability. The choice of the most appropriate method depends on a detailed assessment of the desired protein characteristics, operational costs, and scalability feasibility. This underscores the importance of selecting strategies that minimize negative impacts on functional properties while maximizing process efficiency.

5.2 AMINO ACID PROFILE

Amino acids are essential nutrients for the human body and are often added to foods as nutritional fortifiers and flavor enhancers (Qian et al., 2024). In addition to their nutritional value, they play a crucial role in the functional and technological properties of foods, influencing aspects such as solubility, water-holding capacity, molecular interactions, and exposure of hydrophobic groups (Li et al., 2023; Liao et al., 2024; Qian et al., 2024). They also contribute to structural characteristics, such as particle size reduction, which tends to improve texture, gel strength, and the rheological properties of food products (Li et al., 2023). This effect favors the formation of a more uniform and dense three-dimensional gel network, enhancing the structural integrity and functional performance of plant protein gels (Liao et al., 2024).

Table 3 presents the amino acid profile of common bean (*Phaseolus vulgaris* L.). The non-essential amino acids glutamic acid and aspartic acid are the most abundant. This is expected, as these amino acids are typically present in higher concentrations in legume proteins (Boye; Zare; Pletch, 2010; Iqbal et al., 2006; Sahasrabudhe et al., 1981), mainly due to their central role in nitrogen metabolism in legumes. They act as key intermediates in nitrogen assimilation and redistribution (Ledermann et al., 2024; Virtanen; Laine, 1938). Beyond nutritional relevance, these amino acids are involved in cellular signaling, gene expression regulation, antioxidant responses, immune function, and neurological processes. Therefore, they are frequently used as primary components in amino acid supplements (Brosnan; Brosnan, 2013; Ma et al., 2022; Manta-Vogli et al., 2020; Wu, 2010). Furthermore, they significantly influence sensory properties, such as the umami taste (Brosnan; Brosnan, 2013), and technological functionalities, including protein network formation, primarily through their charge interactions, local interactions, and impacts on secondary structure and protein stability (Herrington; Kellogg, 2021; Roesgaard et al., 2022). Glutamate tends to promote α-helical

regions and increase helicity, whereas aspartate favors extended structures and acts as a helix "cap," influencing flexibility and network formation (Roesgaard et al., 2022).

Tsekova et al. (2024), in their study on the synthesis of two novel anionic gemini surfactants derived from aspartic acid (L-Asp) and glutamic acid (L-Glu) for use as low-molecular-weight gelators, reported that L-Asp can form stable hydrogels over time, classifying it as an effective hydrogelator. In contrast, the L-Glu derivative forms only stable organogels and hydrogels that rapidly self-degrade.

Among the essential amino acids, lysine stands out for its high concentration, which is particularly advantageous since lysine is often the limiting amino acid in plant-based proteins, especially in cereals like rice (Rastogi et al., 2025), while being characteristically abundant in legume proteins (Jafari et al., 2016). Lysine is an essential amino acid that cannot be synthesized by the human body and must be obtained from the diet. It is crucial for protein synthesis and muscle growth, particularly in growing animals and humans (Johansson et al., 2023).

Leucine (532–577 $mg.g^{-1}$) and valine (375–432 $mg.g^{-1}$) were also found in significant concentrations, which is nutritionally relevant since these amino acids are directly involved in protein synthesis and muscle mass maintenance (Xu et al., 2015).

Conversely, tryptophan (57–72 $mg.g^{-1}$) and methionine (89–99 $mg.g^{-1}$) were the least abundant essential amino acids, a common characteristic of legume proteins. Cystine also showed low values (45–75 $mg.g^{-1}$), reinforcing the typical deficiency of sulfur-containing amino acids. Tryptophan is a precursor for neurotransmitters such as serotonin, playing roles in mood regulation, appetite, sleep, immune response, and protection against oxidative stress-induced cell death, including in cancer-related processes (He; Wu, 2020; Liu et al., 2023). Both cysteine and methionine, which contain sulfur, are vital for protein synthesis, antioxidant defense, and cellular detoxification. Cysteine is a precursor of glutathione, one of the body's main antioxidants, while methionine is crucial for initiating protein synthesis and regulating cellular metabolism (Xu; Chen; Liu, 2017). This profile suggests that, from a nutritional perspective, supplementation with complementary protein sources rich in these limiting amino acids, such as cereal proteins, may be necessary to ensure an adequate balance of essential amino acids.

Overall, the results indicate that the evaluated protein has a favorable amino acid profile, with high levels of lysine, leucine, valine, and isoleucine, but limitations in sulfur-containing amino acids and tryptophan. Additionally, the high contents of glutamic acid, aspartic acid, arginine (433–516 $mg.g^{-1}$), and proline (418–447 $mg.g^{-1}$) may positively contribute to certain technological properties, particularly in the formation and stabilization of gels, emulsions, and

foams, as these amino acids are associated with intermolecular interaction capacity and water retention (Qian et al., 2024). Amino acids such as arginine, histidine, and proline can significantly reduce protein turbidity and have been reported to substantially enhance gel strength (Qian et al., 2024).

Table 3 – Amino acid profile of common bean (*Phaseolus vulgaris*)

Amino acids	mg of amino acid per g of sample
Tryptophan	57-72
Lysine	509-599
Histidine	196-224
Arginine	433-516
Aspartic acid	652-762
Asparagine	202-343
Threonine	257-317
Serine	265-293
Glutamic acid	721-842
Glutamine	147-303
Proline	418-447
Glycine	233-299
Alanine	273-340
Cystine	45-75
Valine	375-432
Methionine	89-99
Isoleucine	318-355
Leucine	532-577
Tyrosine	171-187
Phenylalanine	371-395

Source: Sahasrabudhe et al. (1981).

5.3 COMPOSITION AND STRUCTURE OF PROTEINS

In common beans (*Phaseolus vulgaris* L.), the main storage proteins belong to the 7S and 11S globulin classes, with phaseolin being the predominant globulin, accounting for approximately 30–50% of the total seed protein content (Carbonaro; Nucara, 2022; Luna-Vital et al., 2015). Phaseolin exhibits a trimeric quaternary structure and is partially glycosylated (Luna-Vital et al., 2015). Structurally, both globulins found in beans are oligomeric but differ in their molecular organization. Vicilins (7S), with molecular weights ranging from 145 to 190 kDa, form trimers that contain carbohydrate fractions but lack sulfhydryl groups, preventing the formation of disulfide bonds between their subunits (Shevkani et al., 2019). In contrast, legumins (11S) are hexamers composed of two stacked trimers, with a total molecular weight ranging from 300 to 400 kDa, and are stabilized by interchain disulfide bonds (Choe et al., 2022; Shevkani et al., 2019).

The subunits of these globulins are strongly stabilized by covalent and non-covalent interactions, conferring high structural stability and making them relatively resistant to denaturation. Consequently, they are classified as “hard” proteins (Choe et al., 2022).

Studies conducted by Sathe and Salunkhe (1981) on white beans showed that approximately 88.7% of the proteins are globulins and 11.3% are albumins, values expressed on a dry weight basis. These proteins are characterized by high lysine content but are deficient in sulfur-containing amino acids, a typical profile for legume seeds (Sahasrabudhe et al., 1981).

Despite their structural differences, 7S and 11S globulins play distinct roles in functional properties. The 7S fraction exhibits high solubility over a wide pH range and excels in emulsion stabilization, whereas the 11S fraction demonstrates superior gelation capacity and thermal stability. The addition of salt (NaCl) has opposite effects on these fractions: while 7S forms stronger gels in the presence of salt, the gel strength of 11S tends to decrease (Johansson et al., 2023; Kimura et al., 2008).

In general, globulin solubility is highly dependent on pH and ionic strength. These proteins exhibit low solubility near their isoelectric point (pI ≈ 4), due to reduced electrostatic repulsion and enhanced hydrophobic interactions, which promote aggregation and precipitation (Johansson et al., 2023; Lawal et al., 2005). Conversely, under alkaline conditions (pH > 7), there is greater ionization of functional groups, including those originally located within hydrophobic regions of the molecule, leading to partial unfolding of the native structure. As a result, the exposure of polar and charged groups increases, enhancing electrostatic repulsion between polypeptide chains and consequently improving protein solubility (Lawal et al., 2005; Lee et al., 2021).

These characteristics confer globulins superior techno-functional properties compared to other protein fractions. Shen et al. (2025) demonstrated that globulins from cowpea and lentil exhibited higher emulsifying activity indices (ranging from 5.8 to 7.9 $m^2.g^{-1}$ of protein) compared to albumins from the same sources (4.7 to 6.5 $m^2.g^{-1}$ of protein). Additionally, in lentils, globulins showed significantly higher emulsion stability (17 minutes) than albumins (10 minutes).

Albumins, in turn, are water-soluble proteins characterized by a conformation rich in α-helices and the presence of cysteine residues, which favor disulfide bond formation. These structural features provide excellent foaming capacity and stability, often surpassing animal proteins such as ovalbumin in forming cohesive and elastic films around air bubbles (Djemaoune; Cases; Saurel, 2019; Yang et al., 2022). Beyond their technological properties, plant albumins exhibit bioactive properties, including antioxidant activity and inhibitory effects

on enzymes related to metabolic health (Arise et al., 2021; Zheng et al., 2019), expanding their potential use in functional food formulations.

5.4 PHYSICOCHEMICAL AND TECHNO-FUNCTIONAL PROPERTIES

The physicochemical and functional properties of plant proteins are essential for the development of innovative and high-quality food products, especially in response to the growing demand for plant-based diets. Attributes such as solubility, water and oil holding capacity, emulsifying ability, foaming capacity, and gelation directly influence sensory characteristics such as texture and stability, while also affecting the feasibility of industrial processes involved in food manufacturing (Choe et al., 2022; Ge et al., 2023; Johansson et al., 2023; Khan et al., 2025; Kimura et al., 2008; Kumar et al., 2022; Wang et al., 2023).

The functionality of plant proteins can vary depending on several factors, including the botanical source, extraction methods, and processing treatments, which may enhance solubility and improve techno-functional performance (Khan et al., 2025; Náthia-Neves et al., 2025; Qiu et al., 2025). Proteins derived from peas, beans, and lentils have been explored as alternatives to soy protein due to their lower allergenic potential and satisfactory functional performance (Ma et al., 2022).

Additionally, emerging technologies such as ohmic heating and high-pressure processing have proven effective in modulating the functional properties of plant proteins, enhancing their applicability and making them more competitive with animal-derived proteins (Choe et al., 2022; Teng et al., 2025). In this context, detailed functional characterization of these proteins is crucial for guiding their application in specific food formulations such as beverages, baked goods, and plant-based meat analogues. Therefore, a comprehensive understanding and optimization of the functional properties of plant proteins are fundamental to expanding their industrial applications, ensuring both nutritional and technological quality, and meeting the increasing demand for healthier and more sustainable food products.

Despite the promising nutritional profile of white beans (*Phaseolus vulgaris* L.), their techno-functional properties remain relatively underexplored in the scientific literature, especially when compared to other extensively studied legumes such as soy (*Glycine max*) and pea (*Pisum sativum*). In this context, characterizing the functional performance of white bean proteins becomes highly relevant to expanding their potential applications within the food industry. Such understanding may enable their use in emulsified systems, aerated products,

plant-based meat analogues, baked goods, and other technologically demanding formulations, while also contributing to the diversification of commercially available plant protein sources.

Table 4 summarizes the main functional properties of proteins extracted from white beans (*Phaseolus vulgaris*). The evaluation includes key technological attributes such as foaming capacity, emulsifying ability, water and oil holding capacity, gelation, and solubility. These properties are critical for determining the feasibility of incorporating these proteins into various food matrices. The data presented were compiled from studies that highlight the potential of white bean proteins as promising ingredients for the formulation of food products with functional properties, technological appeal, and a sustainable profile.

Table 4 – Techno-functional properties of white bean (*Phaseolus vulgaris* L.) protein and its potential applications in the food industry

Property	Observed Characteristic	Potential Application	Reference
Foaming capacity	Excellent foaming capacity and stability, surpassing commercial proteins such as soy and pea	Cakes, meringues, and aerated desserts	Azevedo et al. (2025); Gundogan e Can Karaca (2020); Tabtabaei et al. (2019)
Emulsification / Oil absorption	High emulsifying capacity and excellent oil-holding ability	Mayonnaise, sauces, and meat products	Azevedo et al. (2025); Bildstein et al. (2008); Costa et al. (2025); Gundogan e Can Karaca (2020); Ramos et al. (2024)
Water absorption	Good water-holding capacity, although potentially lower compared to commercial plant proteins	Bakery products, meat analogues	Azevedo et al. (2025); Tabtabaei et al. (2019)
Gelation	Forms gels at concentrations ≥ 16%	Plant-based gelatin substitutes, desserts	Azevedo et al. (2025); Khan et al. (2025)
Solubility	High solubility (>80%) at acidic (pH 2) and alkaline (≥7) conditions; considerably increases with moderate addition of salt ions	Protein supplements, protein beverages	Azevedo et al. (2025); Ramos et al. (2024)

5.4.1 Solubility

Solubility forms the basis of functional properties, including foaming and emulsifying abilities. In general, protein solubility reflects the thermodynamic equilibrium between protein-solvent and protein-protein interactions, and it may vary depending on environmental conditions, plant species, and extraction methods, which lead to different protein fractions and conformations that ultimately influence solubility (Huang et al., 2024).

The solubility of white bean protein is pH-dependent, exhibiting a typical U- or V-shaped solubility-pH curve, characteristic of legume proteins (Huang et al., 2024; Johansson et al., 2023; Lee et al., 2021; Yang et al., 2023). The lowest solubility is observed at acidic pH (3.0–4.5), corresponding to the protein's isoelectric point (Azevedo et al., 2025; Ramos et al., 2024), where the net surface charge approaches zero. Under these conditions, the reduced surface charge compromises electrostatic repulsion between protein molecules. This proximity promotes hydrophobic interactions and other weak attractive forces, leading to protein aggregation. As a result, solubility decreases significantly, often accompanied by protein precipitation (Costa et al., 2025; Lee et al., 2021).

One of the main limitations of many plant-based protein ingredients is their low solubility (Costa et al., 2025; Huang et al., 2024; Yang et al., 2023). This is commonly attributed to the high content of hydrophobic amino acids, such as leucine, valine, phenylalanine, and proline, in their composition (Khan et al., 2025), which hampers the dispersion of proteins in aqueous systems. This characteristic poses a significant challenge in the development of new products, especially when aiming for desirable texture and stability in food formulations (Costa et al., 2025; Huang et al., 2024; Yang et al., 2023).

Therefore, modulating protein conformation and understanding its functional behavior is crucial, as protein structure directly affects its ability to interact with water and form stable solutions. In this context, improving the solubility of white bean protein concentrates can be achieved by ionic modulation, as demonstrated by Azevedo et al. (2025). In their study, the use of NaCl solutions at concentrations between 0.6 and 0.8 M significantly enhanced protein solubility, attributed to the salting-in effect. This phenomenon occurs when salt ions reduce electrostatic interactions between protein molecules, promoting protein-water interactions and preventing aggregate formation, thereby maintaining the proteins in solution.

5.4.2 Gelation

Globular proteins have the ability to form heat-induced gels through denaturation followed by aggregation, resulting in the formation of a three-dimensional network that retains water. Soy protein is widely recognized for its strong gelling capacity, forming stable gels at concentrations around 8–12% (Chen et al., 2025; Ge et al., 2023; Hu et al., 2025; Nicolai; Chassenieux, 2019; Qiu et al., 2025). However, for white bean proteins, the minimum gelation concentration tends to be higher (Azevedo et al., 2025; Khan et al., 2025; Moreno et al., 2022). Experimental trials indicate that white bean protein dispersions require concentrations above

16% to form solid gels after heating followed by cooling. At concentrations equal to or below 10%, no well-defined gel network was observed, with only an increase in system viscosity. Conversely, in the range of 16% to 20%, the resulting gels exhibited firm and cohesive structures, suggesting that white bean proteins are capable of forming relatively rigid networks (Azevedo et al., 2025).

Additionally, a study conducted with a low-lectin white bean variety demonstrated that, at neutral pH, formulations containing 14% and 17% protein resulted in gels that were less rigid but more elastic and homogeneous, with a white appearance favorable for application in plant-based meat analogs (Moreno et al., 2022). These results suggest that although gelation is feasible, the gelling behavior of white bean proteins is more complex compared to commercial proteins such as soy. This behavior may be associated with the composition of protein subunits (particularly the 7S/11S ratio), the nature of the aggregates formed, and the amino acid profile. Therefore, the gel-forming capacity of white bean proteins is highly sensitive to processing conditions but can be modulated to meet specific requirements of the food industry.

5.4.3 Water Absorption Capacity

Water absorption capacity (WAC) can serve as an indicator of water-binding properties, reflecting the degree of interaction between proteins and water molecules (Tabtabaei et al., 2019). This factor directly influences characteristics such as viscosity and texture in food products (Khan et al., 2025). In the case of white bean protein concentrate, its WAC has been observed to be slightly lower compared to soy and pea proteins. This suggests that white bean proteins interact somewhat less with water, possibly due to a lower presence of exposed hydrophilic subunits (Azevedo et al., 2019).

White bean protein, in its native form and obtained via conventional extraction methods, generally exhibits lower water absorption capacity compared to other protein sources (Khan et al., 2025; Azevedo et al., 2025; Costa et al., 2025). Studies evaluating WAC of white bean protein isolates report similar values. Khan et al. (2025) found that protein isolated through conventional alkaline-acid extraction showed a WAC of 1.30 $g.g^{-1}$, suggesting limited exposure of hydrophilic sites. Conversely, emerging extraction methods resulted in higher WAC values, reaching up to 2.24 $g.g^{-1}$, possibly due to particle size reduction, which favors water interaction, increases solubility, and improves protein dispersion (Wang et al., 2023). Similarly, Ramos et al. (2025) reported a WAC of 1.37 ± 0.12 $g.g^{-1}$ for white bean protein isolate. Additionally, Gundogan and Can Karaca (2020), evaluating different white bean varieties, observed WAC

values ranging from 1.8 to 2.1 $g.g^{-1}$.

Tabtabaei et al. (2019), in a study with white bean (marinho) protein isolate and fractions, reported WAC values of 189.3% for the isolate and 131.8% and 134.5% for the fractions. Comparatively, protein fractions from white bean may present lower water absorption capacity than isolates or concentrates obtained by wet fractionation, as well as compared to soy proteins. This difference can be attributed to a higher availability of polar amino acids exposed on the protein surface, which favors interactions with water (Tabtabaei et al., 2019).

Overall, the water absorption capacity of white bean proteins tends to be lower than that observed in other protein sources, especially when obtained by conventional extraction methods. However, emerging techniques have shown potential to significantly enhance this functional property (see Section 5.1 and 7), possibly due to increased exposure of hydrophilic groups and particle size reduction. Furthermore, low WAC is often associated with reduced availability of exposed polar groups, which diminishes water interaction. This limitation may impair hydration, solubility, and protein dispersion, impacting its application in food products requiring moisture retention, such as emulsions, baked goods, and restructured meat products. Therefore, modification of extraction conditions emerges as a strategy to improve the technological functionality of white bean proteins for various industrial applications.

5.4.4 Emulsification and Oil Absorption Capacity

Globular proteins, such as those from white beans, can act as emulsifiers by positioning themselves at the oil/water interface, with appropriate hydrophobic and hydrophilic regions. Emulsifying capacity (EC) is defined as the maximum amount of oil that can be emulsified by a given amount of protein and is expressed as g oil/g protein (Gundogan; Can Karaca, 2020). Comparative studies indicate that white bean protein extracts exhibit good emulsifying capacity and emulsion stability, comparable to commercial plant-based proteins. In a study comparing white bean protein concentrate (WBPC) to soy protein isolate and pea protein concentrate, Azevedo et al. (2025) observed that white bean proteins formed stable emulsions, along with a high oil absorption capacity (OAC), surpassing those of soy and pea proteins. This indicates a strong affinity of white bean proteins for non-polar molecules (Azevedo et al., 2025; Ramos et al., 2025), which is advantageous for formulations such as vegan mayonnaise, sauces, and processed meat analogs, where plant proteins need to stabilize fats.

The emulsifying capacity (EC) of white bean proteins has been reported to be high in several studies. Gundogan and Can Karaca (2020) reported that white bean protein isolates

exhibited EC values ranging from 402.7 g oil.g^{-1} protein to 468.5 g oil.g^{-1} protein, highlighting their potential in emulsion stabilization.

Similarly, Tabtabaei et al. (2019) reported that the OAC of white bean protein isolate reached 300.3%, which was higher than that of commercial soy protein concentrate and other protein-rich fractions. Ramos et al. (2024) also found OAC values for white bean proteins ranging from 4.0 to 5.4 g oil.g^{-1} sample. This high oil-binding capacity appears to be a characteristic of the bean family (Costa et al., 2025; Azevedo et al., 2025; Ramos et al., 2025; Tabtabaei et al., 2019). Furthermore, the authors reported that the emulsifying activity index of these isolates was high (~68.4%), closely approaching that reported for commercial soy protein isolate (Soybean Supro 500E), which is around 72.0%. This suggests that white bean proteins can function as effective binding agents in various food products, including meat emulsions (Tabtabaei et al., 2017).

Khan et al. (2025) reported that, similar to WAC, the OAC of white bean proteins can be further improved when extracted using emerging techniques such as ultrasound. Using conventional extraction, white bean protein exhibited the lowest OAC (1.80 g oil.g^{-1}), suggesting minimal structural modification and limited exposure of hydrophobic groups necessary for oil binding. However, extraction assisted by ultrasound significantly enhanced OAC compared to EC, with maximum values reaching 3.33 g oil.g^{-1}, an improvement of 86%. This enhancement is likely attributed to ultrasound-induced structural modifications that increase the availability of oil-binding sites.

These findings clearly demonstrate the potential of white bean proteins as effective emulsifying agents for the food industry. Their high oil absorption capacity and good emulsion stability, comparable or even superior to commercial plant proteins, reinforce their applicability in products such as vegan mayonnaise, sauces, and processed meats. Additionally, the ability to further optimize these functional properties through emerging technologies like ultrasound extraction expands the potential for white bean proteins to serve as sustainable, functional, and versatile ingredients in food formulations.

5.4.5 Foam Formation

White bean protein concentrate exhibits remarkable foaming capacity (FC), surpassing that of soy and pea proteins at neutral pH. At pH 7, the foam volume generated by white bean protein solutions was higher, and more importantly, the foam stability (FS) was excellent, maintaining approximately 94% of the initial volume after 30 minutes and around 80% after 60

minutes. This performance was significantly superior to pea protein and comparable to soy (Azevedo et al., 2025). Interestingly, under acidic conditions (pH 4), white bean proteins also demonstrated high foam stability, although the total foam volume was reduced due to lower solubility near the isoelectric point (pI). These results suggest that white bean proteins are highly effective at incorporating air and stabilizing foams in food systems.

Gundogan and Can Karaca (2020) reported high foaming capacity in white bean protein isolates, with values ranging from 72% to 91%. This performance is attributed to an increase in surface net charge, which enhances protein adsorption at the air/water interface while improving solubility and structural flexibility. These factors reduce hydrophobic interactions between protein molecules. Additionally, the protein isolates exhibited good foam stability, maintaining approximately 86% of the foam after 10 minutes of rest. However, foam stability gradually decreased over time, reaching around 76% after 30 minutes and 68% after 60 minutes.

Ramos et al. (2024) evaluated the foaming properties of white bean proteins at different pH levels. At lower (pH 3) and higher (pH 7) pH values, conditions further from the pI, the protein carries higher net charges, weakening intermolecular electrostatic interactions, which increases protein flexibility at the interface and improves foam formation. Conversely, at pH 5, close to the isoelectric point, the lower solubility of proteins resulted in reduced FC.

Overall, these findings demonstrate that white bean proteins perform excellently in foaming systems, particularly at pH values distant from their isoelectric point, where they exhibit higher solubility and greater structural flexibility. The ability to form and maintain stable foams under both neutral and acidic conditions positions white bean protein concentrate as a promising ingredient for aerated food products, reinforcing its potential as a functional and versatile alternative for the food industry.

6 APPLICATION OF WHITE BEAN PROTEIN IN THE FOOD INDUSTRY

Plant-based proteins, in the forms of flours, concentrates, isolates, hydrolysates, and textured proteins, represent a versatile class of ingredients widely employed in the formulation of food products. The growing demand for alternative and sustainable protein sources has driven the development of novel ingredients with improved technological and nutritional properties. In this context, white bean (*Phaseolus vulgaris* L.) has emerged as a promising legume due to its high protein content, balanced amino acid profile, and relevant functional potential.

The incorporation of white bean proteins into processed foods aligns with the clean label

trend and the expansion of the plant-based products market. Furthermore, their use contributes to diversifying protein sources, reducing dependence on conventional crops such as soy and pea, and positioning white bean as a viable alternative from both technological and nutritional perspectives.

Although some studies have explored the use of bean-derived proteins in applications such as edible films, meat analogues, dairy alternatives, and baked goods (Choudhury et al., 2025), the use of white bean protein concentrates and isolates remains limited in the context of processed food formulation. In contrast, white bean flours have been more extensively studied, particularly in bakery products (Barros et al., 2018; Nörnberg; Storck, 2022) and plant-based cheese analogues (Espírito Santo et al., 2022), highlighting a promising potential yet to be fully exploited.

Nörnberg e Storck (2022) evaluated breads with 30% wheat flour replaced by white bean flours (WAF75 and WAF141). Compared to wheat, bean flours had lower energy and higher protein (19.7–23.3%), fiber (21–25.4%), and ash (3.6–3.8%). Technologically, breads showed increased hardness but unchanged flexibility and good sensory acceptance (>70%) in color, aroma, texture, and flavor. The substitution effectively enhanced nutritional quality without compromising consumer acceptance.

Barros et al. (2018) investigated the effect of partially replacing wheat flour with flours from different bean varieties (30%), including white bean, in muffin formulations. The results showed that this substitution improved yield compared to the control and reduced weight loss during baking, a characteristic associated with the higher water-holding capacity of bean flours. Nutritionally, muffins made with bean flours exhibited higher levels of minerals (1.28%), proteins (11.52%), dietary fiber (7.63%), and total phenolic compounds (30.34 mg gallic acid equivalents 100 g^{-1}) compared to the control formulation (1.16%, 10.17%, 3.71%, and 19.16 mg gallic acid equivalents 100 g^{-1}, respectively). Sensory evaluation indicated that muffins with 30% white bean flour replacement showed acceptance, purchase intention, and preference levels comparable to conventional muffins. Therefore, the partial replacement of energy-dense ingredients like wheat flour with white bean flour is a viable strategy for developing bakery products with enhanced nutritional quality and high consumer acceptability, without negatively affecting the final product cost.

Another example of a product developed from white beans was reported by Espírito Santo et al. (2022), who formulated a plant-based cheese analogue incorporating inulin. The formulations showed relevant contents of proteins, fibers, and total lipids, outperforming, in particular, some commercial plant-based cheese products that often have low or negligible

protein content. These findings demonstrate the feasibility of producing a plant-based cheese alternative with improved nutritional and functional properties using legumes as a raw material.

7 CHALLENGES OF APPLYING WHITE BEAN PROTEINS IN THE FOOD INDUSTRY

The development of plant-based protein products poses significant challenges, particularly regarding the selection of protein sources with nutritional profiles comparable to animal proteins, as well as the need for technological advancements in extraction, purification, and functional modification processes. In this context, the main goal of research in this area is to enable the formulation of alternative protein products that combine adequate nutritional quality with sensory appeal, economic feasibility, and high consumer acceptance.

Despite the growing interest in plant-based proteins, these proteins present considerable physicochemical limitations that can hinder their application in various food matrices. Among the main challenges are their low solubility, which limits incorporation into liquid systems, and their tendency toward aggregation, compaction, and high structural rigidity, factors that compromise their effectiveness as interfacial stabilizers. Specifically, white bean protein in its native form exhibits limited technological performance, characterized by low solubility, reduced yields, and restricted functional properties such as poor gelling capacity. These characteristics underscore the need for structural and functional modifications to enhance its application potential in food formulations.

To improve the techno-functional properties of legume-derived proteins, several emerging technologies have been investigated, including ohmic heating (OH), pulsed electric fields (PEF), cold plasma, and ultrasound. These strategies have shown potential to modify protein conformational structures and enhance functional properties, leading to improvements in solubility, emulsifying capacity, and other desirable attributes for food system applications (Khan et al., 2025; Li et al., 2023; Náthia-Neves et al., 2025).

Choe et al. (2022) evaluated the effects of post-extraction treatments (pH adjustment, pH combined with ultrasound, and pH combined with heating) on *Phaseolus vulgaris* protein concentrate. All treatments reduced sulfhydryl groups, indicating structural modifications. Protein solubility increased at pH 6.0, especially with the pH-S treatment. The emulsifying activity index (EAI) improved in all treatments (from 8.2 to up to 23.9 $m^2 \cdot g^{-1}$), but only the pH-SH treatment enhanced the emulsifying stability index (ESI) from 27.2% to 60.7%. pH-SH also increased foaming capacity, although with reduced foam stability. The study highlighted that

structural modifications directly affect the functional and interfacial properties of the protein.

Avelar et al. (2024) evaluated ohmic heating (90–150 °C) on pea protein (PP) solubility, observing an increase of up to 240% at 150 °C. The treatment promoted conformational rearrangement and dissociation of insoluble aggregates. Above 110 °C, possible peptide bond cleavage generated soluble aggregates and low molecular weight peptides. OH proved effective in enhancing PP solubility and expanding its food applications.

Teng et al. (2025) reported that high-intensity pulsed electric fields (60 $kV \cdot cm^{-1}$) reduced chickpea protein aggregation (~60% smaller particles) and induced unfolding, exposing hydrophobic regions. These changes doubled solubility, increased foaming capacity (106% to 160%), and enhanced emulsion stability by 2.7 times, confirming PEF's effectiveness in improving protein functionality for food applications.

Considering the functional limitations of native white bean protein, the application of these technologies represents a promising strategy to expand its industrial utilization and nutritional value.

8 FINAL CONSIDERATIONS

White beans (*Phaseolus vulgaris* L.) represent a legume with high nutritional value and significant technological potential for the food industry, especially in light of the growing demand for sustainable, nutritious, and plant-based products. Their composition, rich in proteins, carbohydrates, fibers, and bioactive compounds, combined with relevant techno-functional properties, makes them an attractive alternative to conventional protein sources such as soy and pea.

However, despite this potential, white bean proteins remain underexplored, particularly regarding the in-depth characterization of their physicochemical and techno-functional properties. In their native form, these proteins exhibit limitations, such as low solubility at certain pH ranges, moderate water-holding capacity, and the need for higher concentrations to form gels. On the other hand, they stand out for their excellent emulsifying capacity, foam formation and stability, and oil absorption, functional properties highly desirable for a wide range of food applications. By highlighting the promising functional properties and the broad application potential of white bean proteins (*Phaseolus vulgaris*), the data presented can contribute to fostering interest and encouraging the national production of this legume.

Moreover, the adoption of emerging technologies, such as ultrasound, ohmic heating, and pulsed electric fields, has proven effective in promoting structural modifications in these

proteins, resulting in significant improvements in their functional properties. These strategies represent promising approaches to overcoming the technological limitations associated with white bean proteins, enabling their application in complex food systems and contributing to the development of innovative products aligned with sustainability goals.

Therefore, this overview demonstrates that fully harnessing white beans as a protein source still requires further research efforts, both in optimizing extraction methods and functional modification processes, as well as in validating their application in different food matrices. Advances in this field can significantly contribute to diversifying the available plant-based protein sources, while also fostering more sustainable, economically viable, and nutritionally safe production chains.

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ARTICLE 2

Techno-Functionalities of White Bean Protein Concentrate: A Comparative Study with Soy and Pea Proteins

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Abstract: The study of the techno-functional properties of novel plant-based proteins has gained importance due to their as alternatives to conventional proteins in food systems. This work evaluated the techno-functional and structural properties of white bean protein concentrate (WBPC) in comparison with commercial soy and pea proteins. The WBPC exhibited a higher foaming capacity (FC) at neutral pH and excellent foam stability (FS) at both tested pH levels, outperforming the commercial proteins. Although the WBPC's gelation occurred only at concentrations above 16% and its water-holding capacity (WHC) was lower than that of the soy and pea proteins, the WBPC showed a high binding capacity for nonpolar molecules, excelling in its oil-holding capacity (OHC) and forming stable emulsions, which are relevant for stabilization in food products. Additionally, WBPC can form more rigid gel networks, suitable for systems requiring greater mechanical strength. These techno-functional properties indicate that WBPC is a promising alternative source for the plant-based food industry, helping to meet the demand for innovative, sustainable products and contributing to the diversification of protein sources.

Keywords: alternative proteins; *Phaseolus vulgaris* L.; foam capacity; emulsion stability; vegetable proteins

1. Introduction

The accelerated growth of the plant-based product market has driven the need for further studies on new protein sources and the impacts of both traditional industrial processes and emerging technologies on these sources [1–7]. Therefore, research on these proteins is crucial to elucidate the potential of their properties, as plant proteins represent a sustainable and economically viable option compared to animal proteins [8,9].

Legume proteins, such as those found in beans, lentils, soybeans, and peas, play an essential role not only as nutritional sources but also due to their techno-functional properties, which make them valuable for various industrial applications [10]. These proteins exhibit attractive technological properties, including good water-holding capacity, foam formation ability, and emulsifying activity, characteristics that position them as promising ingredients for widespread use in the food industry [10–13]. The techno-functional properties of these proteins underscore their potential as innovative alternatives for the development of food formulations, while also contributing to sustainability within the food sector. Understanding these properties is crucial to fully exploring the potential of legumes in various contexts, highlighting their importance in the realm of techno-functional applications.

Among the most extensively studied plant proteins, soy protein is the standard for both the isolated and concentrated forms due to its high availability, high protein content, and favorable functional properties, such as its water-holding capacity, solubility, and hydrophobicity [4,13]. These proteins are widely used in processed meats, plant-based beverages, and meat analogs [14,15]. Recent research efforts have expanded the horizon for new alternative plant proteins [6,7,16–19] due to concerns about allergenicity, the presence of antinutritional factors, and considerations regarding the environmental impact and sustainability associated with soy use [20,21].

Beans are an accessible and economical source of proteins, carbohydrates, dietary fibers, vitamins, minerals, and phenolic compounds. They are an essential component of vegetarian and vegan diets, as the only plant-based food providing a significant amount of the essential amino acid lysine. Moreover, beans are gluten-free, making them an excellent fortifying ingredient in various food products [22]. Bean proteins are characterized by their balanced amino acid content, with high amounts of proline, glutamic acid, arginine, leucine, tryptophan, tyrosine, lysine, and phenylalanine [17,23–25]. Despite the numerous health benefits of beans, such as reducing cardiovascular disease risk factors and promoting gut microbiota health [22], beans remain underexplored legumes regarding their techno-functional properties [26].

Characterizing, modifying, and exploring the use of white common bean protein concentrate represents an important research area in the food industry, as it may serve as a useful protein source for flexitarian, vegetarian, and vegan consumers. Thus, the purpose of this research is to investigate the techno-functional characteristics of white bean protein concentrate (*Phaseolus vulgaris* L.), comparing it with commercial proteins (soy and pea), to broaden the potential for developing food products with technologically modulated ingredients.

2. Materials and Methods

2.1. Extraction and Preparation of Protein Concentrate

The method used to extract the protein concentrate involved alkaline extraction with 1 M NaOH followed by isoelectric precipitation using concentrated HCl. The process of extraction and preparation of white bean protein concentrate is shown schematically in Figure 1. Initially, 100 g of raw white beans was submerged in 1 L of distilled water (ratio 1:10 $w.w^{-1}$) and soaked for 12 h at room temperature. Subsequently, the beans were blended and filtered, and the fibrous portion was discarded. The aqueous portion was adjusted to an alkaline medium (pH 10) for enhanced protein solubilization, followed by agitation for 12 h. The sample was then centrifuged at 10,000 rpm at 4 °C for 20 min. The sediment was discarded, and the supernatant was collected and adjusted to pH 3 for isoelectric precipitation. This supernatant was centrifuged again at 10,000 rpm at 4 °C for an additional 20 min. After this centrifugation, the supernatant was discarded and the precipitate was washed with distilled water (pH 7), then centrifuged again at 10,000 rpm for 20 min at 4 °C. After washing, the white bean protein concentrate was stored in an ultra-freezer for subsequent lyophilization.

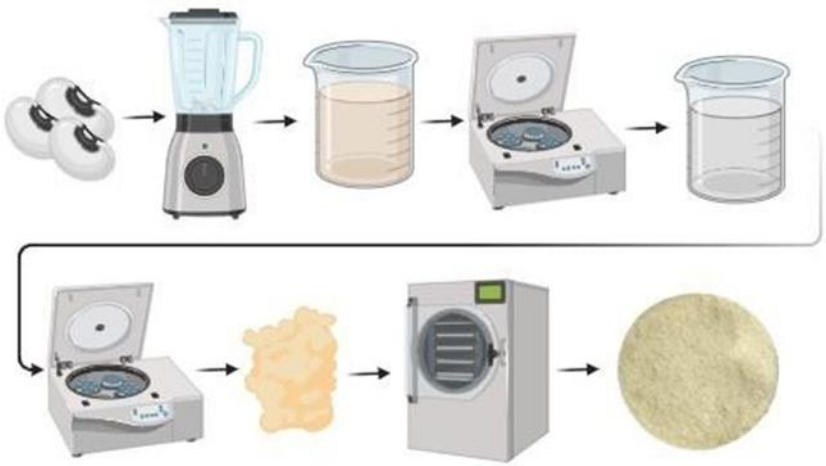

Figure 1. Flowchart of the white bean protein concentrate extraction process. The steps include grinding the beans in a blender (initially on the left), adjusting the pH to 10, centrifugation for fraction separation, subsequent pH adjustment (to 3), a second centrifugation to obtain the precipitated protein, and finally drying the protein concentrate, resulting in a powder.

2.2. Protein Content

The total nitrogen content of the WBPC was determined using a nitrogen-to-protein conversion factor of 6.25 [27].

2.3. Fourier Transform Infrared Spectroscopy

The extracts were analyzed via Fourier transform infrared spectroscopy (FTIR) using an Agilent Cary 630 spectrometer. The FTIR spectrum was collected in the range of 400–4000 $cm^{-}1$ with a spectral resolution of 1 cm^{-1}.

To obtain the values of the secondary structure of the proteins, the FTIR spectra were deconvoluted using the "Peak Deconvolution" application in OriginPRO 2022 through the second derivative method [28].

2.4. Hydrophobicity

The hydrophobicity of the nonsolubilized proteins was determined according to the method described by Chelh, Gatellier, and Santé-Lhoutellier (2006) [29], with minor modifications, using bromophenol blue sodium salt for electrophoresis (from Sigma). In 1 mL of protein suspension, 200 µL of a 1 mg.mL−1 BPB solution (in distilled water) was added, and the mixture was homogenized thoroughly. The control, free of proteins, consisted of adding 200 µL of the same BPB solution (in distilled water) to 1 mL of 20 mM phosphate buffer at pH 7. The samples and control were subjected to continuous agitation in a vortex mixer (Vortex Multi 0-3000 – Craltech) at room temperature for 10 min, followed by centrifugation (Microcentrifuge for microtubes, Daiki – Model DT-10DK) at 10,000 rpm for 10 min. The absorbance of the supernatant (diluted 1.10−1) was measured at 595 nm, using phosphate buffer as the blank. The amount of BPB bound to the proteins was calculated using Equation (1):

$$BPB\ boud = \frac{200\ \mu g\ x\ (A\ control - A\ sample)}{A\ control} \quad (1)$$

With A = absorbance at 595 nm.

2.5. Solubility as a Function of pH, NaCl, and Glucose

The solubility percentage of the WBPC was evaluated based on variations in pH (2.0–10.0), NaCl concentration (0–1 M), and glucose concentration (0–1 M). For the experiment, 3 g of protein was dissolved in 60 mL of distilled water. The pH adjustment was conducted using 1 M HCl and NaOH solutions. For each experimental condition, three 2 mL aliquots were transferred into Eppendorf tubes. Then, 6 mL of distilled water was added to each aliquot to adjust the final pH. In the assays involving varying NaCl concentrations, 1.5 µL of NaCl solution was added to the samples, resulting in concentrations ranging from 0 to 1 M, followed by the addition of 0.5 µL of the protein solution. In the glucose assays, 1.5 µL of glucose

solution was added to reach concentrations ranging from 0 to 1 M, with 0.5 µL of protein solution. The samples were stirred for 1 h at room temperature, followed by centrifugation at 4 °C at 8000× g for 10 min. Then, 2 µL of the supernatant from each tube was pipetted into microplates, and protein quantification was performed using the Bradford method.

2.6. Water-Holding Capacity (WHC) and Oil-Holding Capacity (OHC)

The WHC and OHC of the WBPC were determined following the methodology described by Tan, Ying-Yuan, and Gan (2014) [25], with modifications. The WBPC (0.1 g) was mixed with 1.5 mL of distilled water and with 1.5 mL of soybean oil in a pre-weighed microcentrifuge tube, then vortexed (Vortex Multi 0-3000, Craltech) for 1 min. The sample was incubated at room temperature for 30 min and then centrifuged (Microcentrifuge for microtubes, Daiki, Model DT-10DK) at 10,000 rpm for 30 min. The resulting supernatant was carefully decanted and the sample was weighed. The WHC and OHC were expressed in grams of water or oil bound per gram of sample using Equation (2).

$$WHC/OHC(g\ de\ água\ ou\ óleo/g\ de\ proteína) = \frac{W_2 - W_1}{W_0} x\ 100 \quad (2)$$

where W_0 is the weight of the dry sample (g), W_1 is the weight of the tube plus the dry sample (g), and W_2 is the weight of the tube plus the sediment (g).

2.7. Emulsion Analysis

2.7.1. Emulsion Production

The emulsions were prepared with a fixed concentration of 1 g of protein in two ratios of commercial soybean oil to protein solution (1:1 and 2:1 oil/water) at pH 4 and 7, for a total volume of 30 mL. The mixture was homogenized using a high-speed disperser (Ultra – Turrax IKA T25 digital; Model T 25 D S32) at 25,000 rpm for 90 s, and the emulsion stability was assessed using a Turbiscan Lab.

2.7.2. Turbiscan Analysis

The emulsion stability was measured according to the adapted methodology of Zhu et al. (2020) [30] using the Turbiscan Lab analyzer (Serial Number: 2302 – TL – 2395; SMLS 880 nm; Formulaction, France). This equipment enables separate measurements of the transmission and backscattering of the sample. A 20 mL volume of the emulsion was transferred

into a specific glass test vial for the instrument and subjected to a scan analysis along the height of the tube, performed by two detectors at a temperature of 25 °C. Measurements were taken at 1 min intervals from 0 to 10 min, 2 min intervals from 10 to 20 min, and 5 min intervals from 20 to 60 min, totaling a 1 h continuous analysis. The emulsion stability was determined using the Turbiscan Stability Index (TSI) via the Turbiscan software (TurbiSoft-Lab-3.0.2.0).

2.8. Least Gelation Concentration (LGC)

The least gelation concentration (LGC) of the WBPC was determined as described by the conventional methodology [13]. Protein suspensions with concentrations ranging from 2% to 22% were prepared in 20 mL of distilled water and transferred to sealed glass test tubes. The tubes were subjected to a water bath (Dubnoff Microprocessed Bath – Q226M) at 100 °C for 1 h, followed by immediate cooling in an ice bath and storage at 4 °C overnight. The samples were then inverted and categorized into three gelation categories: (1) absence of gel, indicated by a liquid solution that flowed without resistance; (2) weak gel, characterized by a solution that flowed with some resistance; (3) gel formation, evidenced by a solution that did not flow when the tube was inverted. The LGC was defined as the lowest concentration that formed a firm gel.

2.9. Rheological Analysis

A Haake Mars IQ Air stress- and strain-controlled oscillatory and rotational rheometer (Thermo Scientific Ic., Germany) equipped with a steel parallel plate (35 mm diameter/1 mm GAP) and with a Peltier heating system was applied the dynamic rheological properties of the samples. After the sample was placed on the plate, the temperature was allowed to stabilize for 5 min. All rheological measurements were conducted in triplicate and the average values are reported here.

2.9.1. Dynamic Shear Properties

The amplitude sweep test was performed in the strain range of 0.01–100% at 1 Hz to determine the linear viscoelastic region (LVR). A frequency sweep test was performed at 1.0% strain (within LVR) over a frequency (ω) range of 0.1–10 Hz at 25 °C and the temperature sweep test at 25–95–25 °C at the same heating and cooling rate of 5 K/min at 1 Hz of frequency to record the storage (G’), loss modulus (G’’), tangent phase (tan δ), and complex viscosity (η*) values.

The dependence of *G'*, *G''*, and η^* of the samples on the angular frequency (x) was modeled by a power-type relationship (Equations (3)–(5)) and on the temperature by an Arrhenius model (XX):

$$G' = K'(\omega)^{n'} \quad (3)$$

$$G'' = K''(\omega)^{n''} \quad (4)$$

$$\eta^* = K^*(\omega)^{n^*} \quad (5)$$

where *K'*, *K''*, *K**, *n'*, *n''*, and *n** are empirical constants [31].

2.10. Foam Capacity (FC) and Foam Stability (FS)

The foaming properties of WBPC were determined according to the method of Ge et al. (2024) [23], with minor modifications. Approximately 0.3 g of WBPC was dispersed in 10 mL of deionized water adjusted to pH 4 and 7, using 0.1 M HCl or NaOH. The dispersion was whipped at 25,000 rpm for 90 s using a high-speed disperser (Ultra – Turrax IKA T25 digital; Model T 25 D S32). The foam volume (mL) was recorded from 0 to 60 min. The FC and FS were calculated using Equations (6) and (7), respectively:

$$FC(\%) = \frac{V_1}{V_0}\, x\, 100 \quad (6)$$

$$FS\ (\%) = \frac{V_2}{V_1}\, x\, 100 \quad (7)$$

where V_1 is the volume after agitation, V_0 is the initial volume before agitation, and V_2 is the volume after resting.

2.11. Statistical Data Analysis

All analyses were performed in quadruplicate. The results are expressed as the mean ± standard deviation. The mean comparisons were conducted using a one-way analysis of variance (ANOVA), followed by Tukey's test ($p<0.05$). The statistical analyses were performed using JAMOVI software (version 2.4.14).

3. Results and Discussion

3.1. Fourier Transform Infrared Spectroscopy (FTIR)

The FTIR results provide detailed insights into the secondary structure of the analyzed proteins [32]. Table 1 presents the percentage values of the different secondary structures (α-helix, β-sheet, β-turn, and random coil) for the white bean protein concentrate (WBPC), soy protein isolate (SPI), and pea protein concentrate (PPC). It is noteworthy that β-structures were predominant in the secondary structures of all analyzed proteins, with β-sheet being the major component across all proteins, showing no significant differences between them (p-value>0.05). Other isolates and concentrates from various bean varieties also exhibited β-sheet as the main structural component [10,33–35].

Table 1 – Secondary structure of white bean and pea protein concentrates and soy protein isolate.

Sample	α-Helix	β-Sheet	β-Turn	Random Coil
White beans	11.12 ± 0.2c	56.13 ± 1.5a	17.39 ± 0.1b	15.34 ± 0.1a
Pea	12.73 ± 0.3b	55.14 ± 3.2a	19.63 ± 0.2a	12.48 ± 0.1b
Soy	15.03 ± 0.5a	57.22 ± 2.2a	19.63 ± 0.2a	8.10 ± 0.3c

Source: Authors' own elaboration (2025).
The letters a, b, and c indicate significant differences between the data in the same column (p-value < 0.05).

The β-sheet content may be associated with the hydrophobic interactions of the protein, as hydrophobic sites present in the molecule can be exposed, thereby increasing the surface hydrophobicity [36]. WBPC exhibits the lowest percentage of α-helixes and the highest percentage of random coils compared to the other proteins in this study. The higher random coil percentage in the WBPC may be related to a more disordered protein structure [37,38], with a significant difference (p-value < 0.05) when compared to conventional proteins. The lower α-helix content could also indicate a less ordered protein structure [39] compared to soy and pea proteins, which show higher percentages (p-value<0.05) of α-helixes, suggesting a more compact and stable conformation for these proteins. This difference may explain the better functional properties observed in their native forms, which will be discussed in later sections.

From the results of the secondary structure composition of the proteins, we can begin to understand the stability and potential functionalities of WBPC. Although the structure of soy protein isolate and pea protein concentrate appears more organized, white bean protein exhibits a less defined conformation, which may indicate greater flexibility to changes compared to conventional proteins. These disordered regions of WBPC may facilitate binding with different molecules more easily, and the flexibility could enable structural changes that improve functional properties.

3.2. Surface Hydrophobicity

The surface hydrophobicity of a protein can be understood as a property that relates to the extent of hydrophobic groups exposed on the protein surface [40,41]. Figure 2 compares the surface hydrophobicity of white bean protein concentrate (WBPC) with commercial soy protein isolate (SPI) and pea protein concentrate (PPC). The results indicate that PPC exhibits greater hydrophobicity compared to the other proteins, likely due to a higher amount of nonpolar regions exposed on the surface of the pea protein.

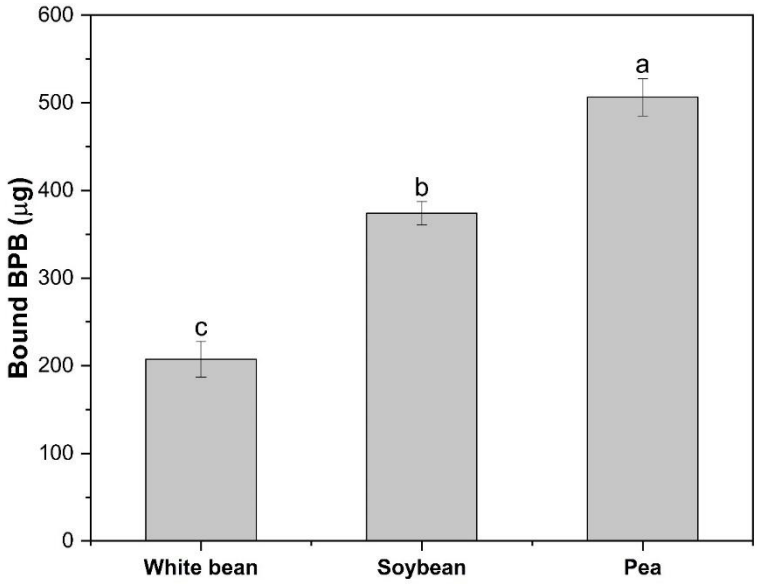

Figure 2. Surface hydrophobicity of white bean protein concentrate compared with commercial soy protein isolate and pea protein concentrate. The letters a, b, and c indicate significant differences between the data in the same column (p-value < 0.05). Bound BPB refers to the amount of Bromophenol Blue bound to proteins, with the unit of measurement expressed in micrograms (µg), indicating the quantity of this substance or the complexes formed.

In contrast, WBPC shows significantly lower hydrophobicity (p-value<0.05) when compared to the commercial proteins. More hydrophobic proteins tend to exhibit better emulsifying properties due to their ability to adsorb at the oil–water interface, as well as a high capacity for foam formation, since hydrophobic regions aggregate at air–water surfaces [42]. Conversely, proteins that are more hydrophilic typically bind more readily to water molecules, which imparts resistance to precipitation and aggregation.

Although hydrophobicity is generally associated with improved interaction of the protein with nonpolar molecules [33,40,43], oil retention may be favored by less hydrophobic proteins, which tend to be more flexible and present a larger contact surface, facilitating interaction with oil, depending on its polarity [44]. Another relevant factor is that the flexibility of less hydrophobic proteins may enhance the interaction with water, resulting in better

solubility, which favors air retention. Consequently, these proteins can exhibit a good capacity for foam formation [12] by reducing the coalescence rate of bubbles.

While WBPC has lower hydrophobicity compared to commercial plant proteins, this does not necessarily imply reduced effectiveness in functional properties within food systems that rely on protein–oil and protein–water interactions.

3.3. Solubility

3.3.1. Solubility as a Function of pH

Understanding protein solubility is essential, as it is linked to the performance and properties of proteins in high-moisture food systems [7,23,40,43,45]. Figure 3 presents the solubility results for WBPC as a function of pH variations. WBPC's solubility is shown to be strongly pH-dependent, with minimum solubility observed at pH 3, which can be attributed to its isoelectric point (pI). At this pH, the lowest solubility is due to the minimal net charge of the protein molecules, resulting in reduced electrostatic repulsion and leading to protein aggregation. Conversely, maximum solubility occurs in highly acidic (pH 2), neutral (pH 7), and alkaline (pH 8 and 10) environments, where surface charges promote electrostatic repulsion between protein molecules, preventing aggregation and precipitation. These conditions enhance protein–solvent interactions, thereby increasing solubility [7,11]. When applied to food systems, higher protein solubility enhances water interactions, improving properties such as the water-holding capacity, foam formation, and stability. It may also increase the oil droplet coverage, favoring better stabilization [40].

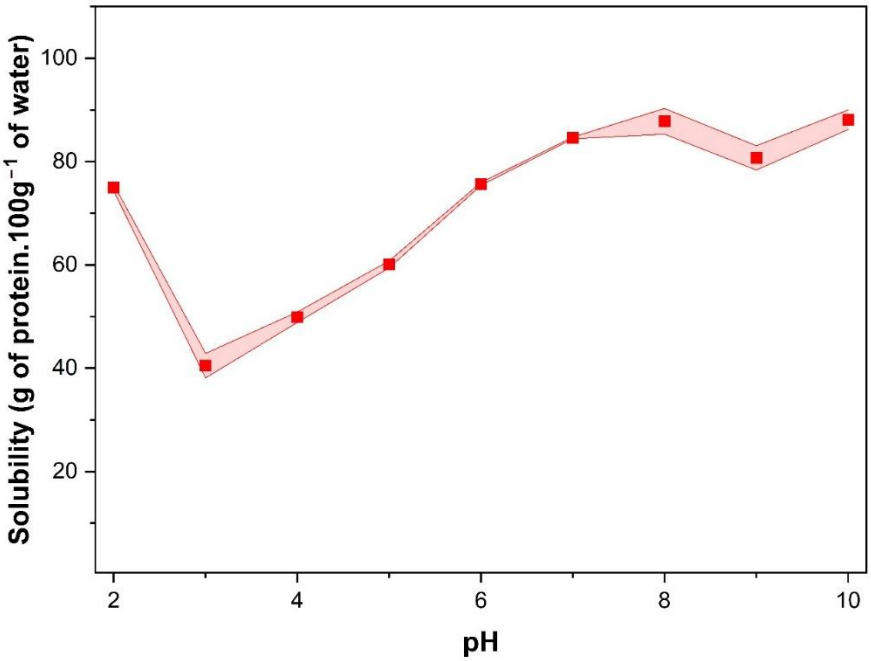

Figure 3. Solubility of white bean protein concentrate as a function of pH variation. Solubility is expressed as the amount of protein (g) dissolved in 100 g of water, showing variation with pH. The points represent the experimental measurements.

3.3.2. Solubility as a Function of Salt (NaCl) Concentration

Figure 4 shows the WBPC's solubility as a function of the NaCl concentration, highlighting an initial increase with salt addition, reaching peak solubility at approximately 0.8 M. This pattern suggests that salt enhances protein solubilization, likely due to the salting-in effect. In this phenomenon, low salt concentrations can increase the protein solubility by reducing electrostatic interactions among protein molecules, facilitating protein–water interactions and preventing protein aggregation [46–49].

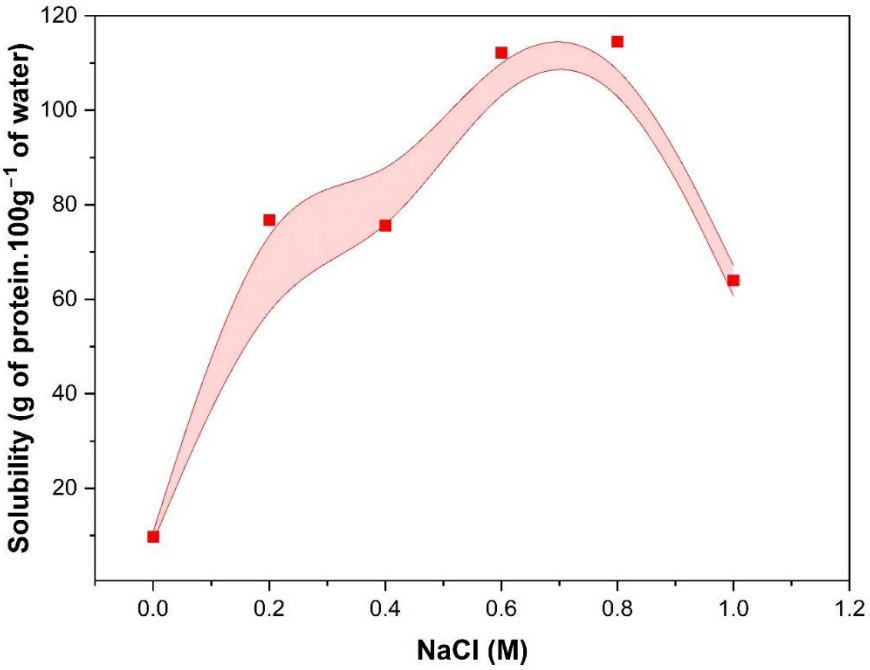

Figure 4. Solubility of white bean protein concentrate as a function of NaCl concentration. Solubility is expressed as the amount of protein (g) dissolved in 100 g of water. The points represent the experimental measurements.

However, as the NaCl concentration surpasses >0.8 M, the solubility declines significantly due to the salting-out effect. At high salt concentrations, water preferentially solvates NaCl ions, reducing its availability to interact with proteins, leading to protein aggregation and precipitation [46–50]. With the addition of 1 M NaCl, the WBPC's solubility reaches a minimum, indicating that further salt additions have no additional effect on the protein solubility.

Studies such as that by Mu et al. (2009) [51] on the influence of salts on sweet potato protein's emulsifying properties demonstrated that adding 0.2 mol.L^{-1} of $CaCl_2$ enhanced the emulsifying activity and stability, reducing the dependency of the emulsifying activity index on the pH. Such correlations between salt and protein solubility could reduce the need for synthetic additives in formulations [52].

Schuldt et al. (2014) [53] reported that the soy protein isolate solubility increased, contributing to the formation of softer gels by promoting electrostatic interactions that enable molecular rearrangements. Additional repulsive forces seemed to promote protein rearrangements, enabling optimal gel network configuration. Furthermore, Yuliana et al. (2014) [48] observed that NaCl concentrations of up to 0.5 mol.dm^{-3} improved the solubility, foam stability, and emulsions of cashew nut shell protein isolate, due to weakened hydrophobic

interactions and protein adhesion, forming interfacial layers with improved rheological properties that enhance the foam and emulsion integrity.

Understanding the effect of the NaCl concentration on protein solubility is relevant for the application of WBPC in food products containing salt. Optimizing the solubility at low salt concentrations can enhance important functional properties [54,55], such as the emulsification and foaming capacity [48], while allowing control and mitigation of the negative effects associated with high ionic strength [54,56]. This understanding also provides a foundation for developing formulations with reduced reliance on synthetic additives, thereby expanding the techno-functional potential of WBPC. The evaluation of this property is common in the analysis of new vegetable proteins [54,56,57], and it is important to understand the behavior of the protein at different NaCl concentrations, as many of these proteins can be applied in the production of meat analogs and hybrid meat products.

These results are significant for the application of WBPC in food products containing salt, providing insights into its behavior in various formulations. The limited solubility of plant proteins, such as WBPC, can be optimized in low-salt solutions, enhancing functional properties such as emulsification and gel formation.

3.3.3. Solubility as a Function of Carbohydrate (Glucose)

Figure 5 presents WBPC's solubility as a function of the glucose concentration, showing fluctuations throughout the curve. Initially, the addition of glucose results in increased solubility, reaching a peak between 0.1 and 0.3 M glucose. This increase can be attributed to glucose's stabilizing effect, as it may form a hydration layer around protein molecules and through hydrophilic covalent bonding, enhancing the interactions between protein molecules and water, thereby promoting solubility [58].

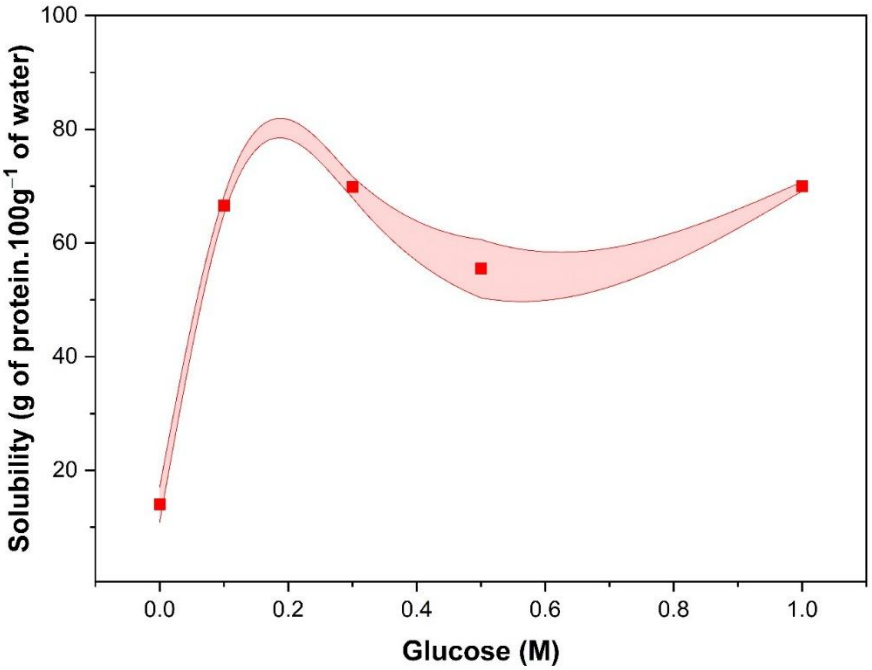

Figure 5. Correlation between glucose concentration (M) and protein solubility (g of protein per 100 g of water): the curve represents the variation in protein solubility as a function of glucose concentration.

Beyond 0.2 M of glucose, the WBPC's solubility decreases, suggesting protein destabilization at intermediate glucose concentrations. This behavior may be explained by the glucose forming a network that competes with the protein for available water, due to glucose's high hydrophilicity. This may enhance the hydrophobic interactions among protein molecules, resulting in decreased protein solubility [59].

At higher glucose concentrations (~1 M), the protein solubility increases again. The presence of hydrophilic or charged carbohydrate fractions can enhance the protein surface hydrophilicity or charge, leading to increased hydration and electrostatic repulsion among protein molecules, which promotes solubility. Additionally, carbohydrates may increase the steric repulsion between proteins, preventing aggregation [60]. Studies indicate that different plant proteins, such as rice protein [61] and pea protein [58], when conjugated with sugars, can show improvements in properties such as solubility, activity, and emulsification stability.

Glucose exhibits a unique effect on the WBPC's solubility, reflecting the complex interaction that can exist between carbohydrates and proteins in aqueous solutions. These findings are particularly relevant for food systems applications, especially given the lack of prior studies on glucose and white bean protein interactions.

3.4. Foam Capacity (FC) and Foam Stability (FS)

The FC values of the WBPC, PPC, and SPI at pH 4 and 7 are shown in Figure 6A. Our analysis of the pH conditions applied to the proteins reveals that the pH acts as a critical factor in foam formation, influenced by parameters such as solubility and the protein's behavior in acidic and basic environments. Under acidic conditions, PPC and SPI exhibit greater foam capacity compared to WBPC. This suggests that these proteins are structurally more flexible and capable of forming foam in this environment. The lower foam capacity of WBPC under these conditions may be associated with its low solubility at this pH, likely due to its isoelectric point (pI) near pH 4, where the electrical charges are reduced and solubility is minimal. Proteins solubilized and precipitated near their isoelectric point tend to show reduced functional properties, such as the FC, at pH values close to the pI, as evidenced by previous studies [62,63].

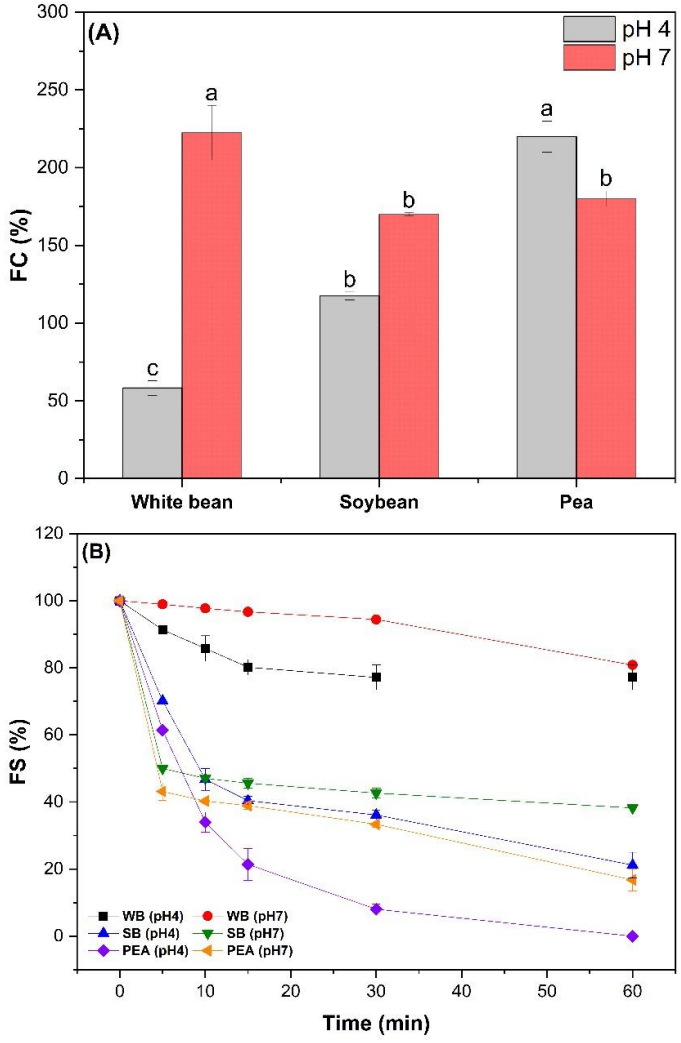

Figure 6. Comparison of foam functional properties at different pH levels and protein sources. (A) Foam capacity (FC%) of proteins from white bean, soybean, and pea at pH 4 and pH 7. Bars represent mean values ± standard error and different letters indicate statistically significant

differences ($p<0.05$) within the same pH range. (B) Foam stability (FS%) over time (0–60 min) for the same protein sources at pH 4 and pH 7. Stability is represented by the remaining foam fraction over time, with distinct symbols used for each condition.

Regarding the FS under acidic conditions, Figure 6A shows that the WBPC demonstrated greater foam stability at pH 4, despite the PPC and SPI exhibiting higher FC in this condition. This behavior may be attributed to the protein's specific interaction with the medium. Although pea protein shows good FC, its stability is considerably lower, with only around 13% stability after 15 min, rapidly decreasing over time and reaching 0% after 60 min, which limits its application in products requiring stable foams. Conversely, WBPC's high stability in acidic environments indicates its potential for application in products that demand high foam stability.

At neutral pH, WBPC exhibits high FC, outperforming the commercial proteins analyzed. This performance may be related to the increased solubility and structural conformation of white bean protein concentrate, favoring foam formation in this environment. While SPI and PPC also demonstrate good foam-forming abilities, both are inferior to WBPC. Regarding the FS, Figure 6B shows that WBPC retains approximately 94% and 80% of its foam after 30 and 60 min, respectively, indicating good performance at neutral pH. Although SPI maintains good stability over prolonged periods and is more stable than PPC, its stability is inferior to that of WBPC, which may limit its efficacy in foods requiring stability at neutral pH. The initial foam formation alone is not a definitive indicator of the food application potential. PPC, for example, experiences a rapid decline in stability at neutral pH even after forming foam initially, with only about 17% of its foam being retained after 60 min, indicating that WBPC may serve as a suitable substitute. Globular proteins such as WBPC can form an interfacial film alongside carbohydrates, allowing air bubbles to be suspended, reducing their coalescence rate, and improving the foam stability [64]. The higher FC at neutral pH may be explained by the increase in the net surface charges of the proteins, related to weakened hydrophobic interactions and increased protein–protein repulsions, resulting in greater flexibility. This flexibility allows proteins to diffuse more rapidly at the air–water interface, effectively encapsulating air particles and enhancing the FC under neutral pH conditions [35,48,62].

Gundogan and Karaca (2020) [35] investigated the FC and FS in bean proteins, which also exhibited good foaming properties. Gouvêa et al. (2023) [13] demonstrated in their study that common bean protein concentrate maintained approximately 95% FS after 60 min, outperforming SPI, which showed significant loss, with less than 65% foam retention. Similar

to WBPC, lupin protein fractions studied by Burgos-Díaz et al. (2016) [63] showed favorable FS and FC under different pH conditions. Additionally, Tang, Roos, and Miao (2023) [65] studied chickpea and lentil protein isolates, revealing these proteins' potential in food foam formulations, independent of the pH, making them promising alternatives to animal-derived proteins.

These results suggest that WBPC could serve as a valuable ingredient for applications in food products. In addition to being an alternative to commercial plant proteins with lower foam stability, WBPC stands out for its efficiency in maintaining the foam structure and volume over prolonged periods, which is beneficial for applications in products such as toppings and confections [13] and beverages such as beer and coffee [62].

3.5. Least Gelation Concentration (LGC)

The least gelation concentration (LGC) values of the white bean protein concentrate (WBPC) at different protein concentrations (2% to 22%) are presented in Figure 7. No gel formation was observed at concentrations between 2% and 10%. Gel formation occurred only at concentrations above 16%, with firm gel formation observed at higher concentrations of WBPC (≥20%). Results similar to those of this study were reported by Gouvêa et al. (2023) [13], who studied the LGC in common beans and found firm gel formation only at the highest concentration (20%). Tan, Ying-Yuan, and Gan (2014) [25] found that when analyzing the LGC in pinto bean protein isolate, a weak gel began forming at 16% and a firm gel at 12% for soybean protein isolate.

However, the LGC of WBPC appears to be higher than that reported by Peyrano, Speroni, and Avança (2016) [66], who investigated cowpea protein isolate with an LGC of 12% without heat treatment, as well as Ogunwolu et al. (2009) [67], who studied cashew protein concentrate (10.0 ± 1.81%) and cashew protein isolate (13.5 ± 0.01%) at their natural pH. This suggests that proteins from other bean varieties and plant protein sources may have lower LGCs compared to WBPC. According to Ma et al. (2022) [43] and Ogunwolu et al. (2009) [67], these LGC variations may be due to the fact that smaller globular proteins generally require higher concentrations to form a gel compared to larger, more extended proteins. Thus, different protein fractions can significantly influence the LGC.

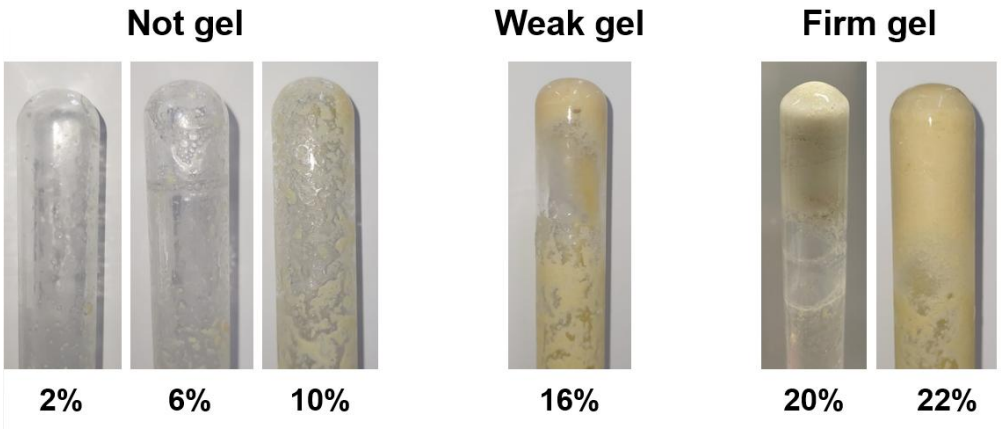

Figure 7. Minimum gelation capacity of white bean protein concentrate. The images represent the behavior of proteins at increasing concentrations (2% to 22%) and the corresponding gel formation. The samples are classified into three categories, absence of gel (2%, 6%, 10%), weak gel formation (16%), and firm gel formation (20%, 22%), indicating the dependence of the protein concentration on gel structuring.

3.6. Gel Rheology

3.6.1. Gel Rheology as a Function of Frequency

The rheological behavior of the WBPC, SPI, and PPC was studied with respect to their oscillation frequency, as shown in Figure 8. In rheology, G', the storage modulus, indicates the material's elasticity, while G", the loss modulus, indicates the material's viscosity [23,45]. Figure 8 illustrates the variations in G' and G" for WBPC as a function of frequency and G' and G" for SPI and PPC. Overall, both moduli increase to different extents at higher frequencies across all protein gels. However, when comparing the WBPC with the conventional proteins analyzed, differences in gel rigidity and structural stability are evident. With an elastic modulus reaching 10 kPa, the WBPC gel has a more rigid structure compared to the weaker, less rigid gels of the commercial proteins.

Rigid gels are advantageous for applications requiring higher resistance to external forces and a more stable structure, such as gelatin and certain desserts. In contrast, less rigid gels are ideal for applications where a firm structure is unnecessary but viscosity and fluidity are desirable.

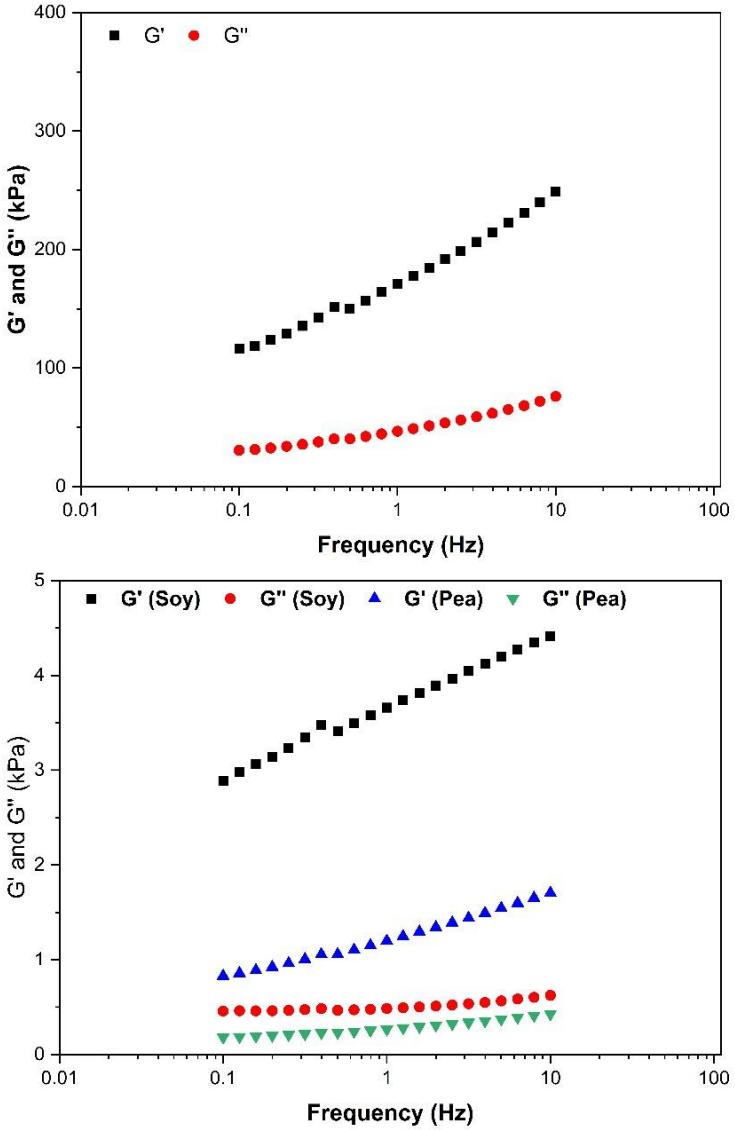

Figure 8. Rheological behavior of white bean, soy, and pea protein gels as a function of frequency. The figures present the elastic (G') and viscous (G") moduli as a function of frequency (0.01–10 Hz) for white bean protein (upper part) and soy and pea proteins (lower part). The results show the rheological dependence of the protein systems, highlighting the formation of distinct structural networks.

3.6.2. Rheological Analysis as a Function of Shear Strain

Figure 9 shows the rheological analysis of the WBPC, SPI, and PPC as a function of shear strain. In Figure 9, which corresponds to the white bean protein concentrate (WBPC), G' > G" across nearly the entire range of shear deformation, indicating predominantly elastic behavior. This profile suggests a rigid network structure (with G' and G" in kPa), characterizing it as a strong gel suitable for applications requiring high mechanical strength and elasticity. However, near 10% deformation, the G' and G" values decline, indicating that at higher deformation levels the gel structure begins to break down, an expected behavior for viscoelastic

materials [45,68,69]. Despite the white bean protein appearing to form a well-defined gel structure, the inflection point between G' and G'' can be considered a stability threshold, where increased shear deformation leads to a loss of the network's mechanical integrity.

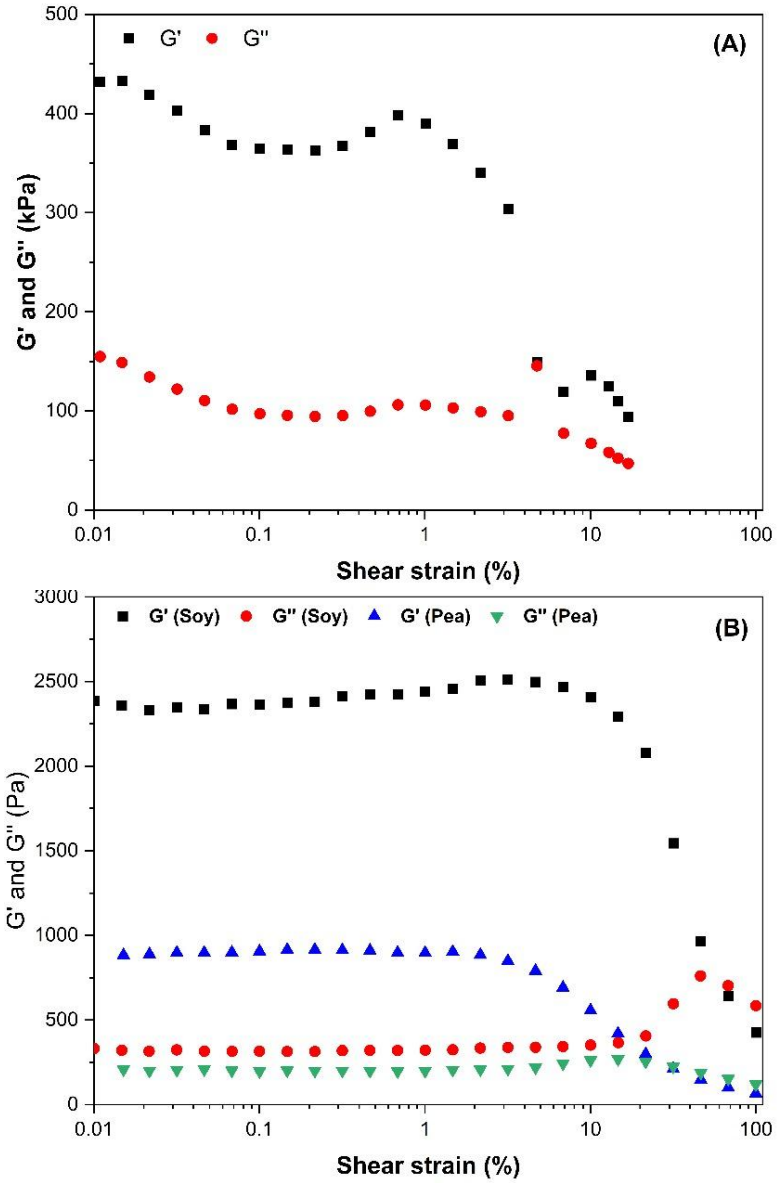

Figure 9. Deformation resistance of white bean, soy, and pea protein gels. The figures present the elastic (G') and viscous (G") moduli as a function of shear strain (%): (A) white bean protein gels; (B) soy and pea protein gels. The analysis demonstrates the structural stability of the gels under increasing deformation, indicating the structural rupture point at different protein concentrations.

In contrast, Figure 9, which displays the shear strain curves for the PPC and SPI, shows that both exhibit elastic behavior. The soy protein has higher G' values, remaining relatively constant up to a greater strain level compared to pea protein, which shows lower G' and G"

values, suggesting a less cohesive and weaker network. This indicates that soy protein forms a more rigid and structured network than pea protein, which likely has lower long-term stability.

These data suggest that soy and pea proteins may offer sufficient structural stability for food applications requiring gels with lower rigidity and greater flexibility. By comparison, white bean protein, with its higher G' and G" values (in kPa), demonstrates a greater potential to form rigid networks depending on the level of shear deformation, making it more suitable for systems that demand high mechanical resistance.

3.7. Water-Holding Capacity (WHC) and Oil-Holding Capacity (OHC)

The WHC and OHC of the analyzed proteins are presented in Figure 10. The WBPC exhibited lower WHC values compared to the SPI and PPC. These variations in WHC may be due to differences in protein structure, the availability of polar amino acids on protein surfaces that interact with water [10,11,70,71], and the presence of hydrophilic carbohydrates that contribute to water absorption [10].

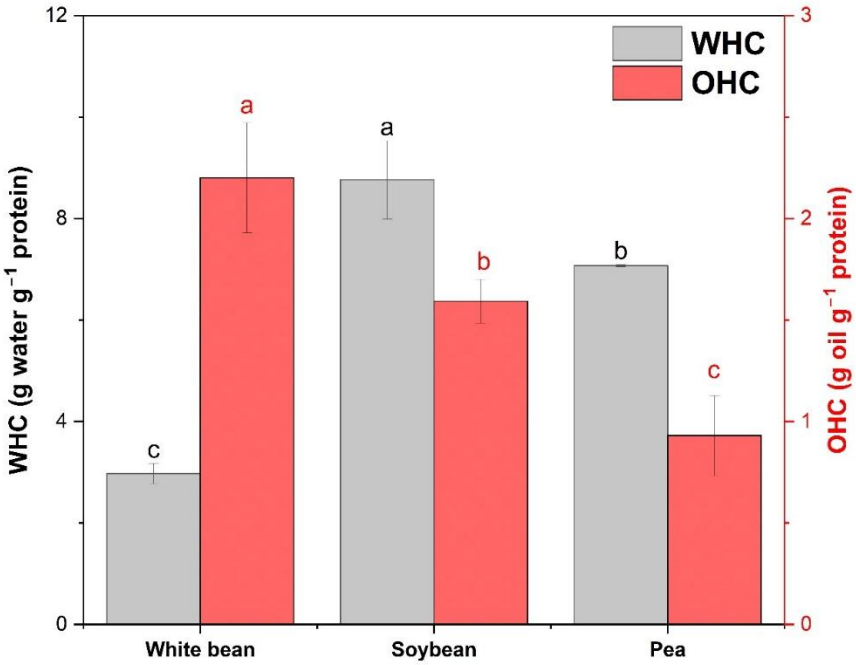

Figure 10. Water-holding capacity (WHC) and oil-holding capacity (OHC) of white bean protein concentrate, pea protein concentrate, and soy protein isolate. The water–holding capacity (WHC) is presented on the left axis (gray bars) and the oil-holding capacity (OHC) on the right axis (red bars). The bars represent the mean ± standard deviation. Different letters indicate statistically significant differences ($p<0.05$) between groups for each evaluated parameter. WHC is expressed in g of water per g of protein, while OHC is expressed in g of oil per g of protein.

In comparison to recent studies on the functional properties of other protein fractions [10,70,72], the WBPC demonstrated a relatively high WHC, highlighting its potential compared to alternative proteins, potentially due to protein unfolding and increased molecular spacing. Enhancing the interaction of these proteins with water can be achieved by applying specific concentrations of salts [46] and sugars [60], which improve the WBPC's solubilization, as observed in this experiment. Furthermore, the use of structural modification through emerging technologies is a promising approach for this purpose [36,73]. However, additional studies are needed to fully explore these possibilities for white bean protein concentrate.

On the other hand, the WBPC showed a significantly higher OHC (p-value < 0.05) than the other proteins (Figure 10). This result is consistent with Lafarga et al. (2018) [74], who reported a high OHC for Ganxet bean protein concentrate, and Tabtabaei et al. (2019) [71], who found that navy bean exhibited a higher OHC than commercial soybean protein concentrate and other protein-rich fractions.

The high OHC may be attributed to denaturation, alterations in surface properties, and exposure of protein hydrophobic groups [23,71,75]. Elevated hydrophobicity enhances oil retention as lipid chains interact with the nonpolar side chains of amino acids. This hydrophobic interaction provides a strong driving force for oil retention, a key component in effective oil binding [23]. Hydrophobicity is considered one of the most significant intrinsic factors affecting the OHC and emulsifying properties in legume proteins [35]. The WBPC's good diffusion at the oil–water interface may be linked to these hydrophobic groups on its protein surface due to the higher presence of β-sheet in its secondary structure.

There is a strong positive correlation between the OHC and the emulsifying capacity and emulsion stability [72]. In the food industry, a protein with good OHC is valuable for use in products and emulsion-stabilizing applications, such as sausages, fat-rich gels, and beverages.

Gouvêa et al. (2023) [13], who also studied a protein concentrate from another bean variety, confirmed that bean proteins have promising potential for the plant-based market due to their better emulsifying activity index than soybean protein concentrate and excellent emulsion stability, surpassing other isolates and concentrates such as soybean, pea, and fava bean. Tan, Ying-Yuan, and Gan (2014) [25], as well as Tabtabaei et al. (2019) [71], also reported high emulsifying capacity for pinto beans and good emulsifying activity for navy beans, respectively.

3.8. Emulsion Stability

The Turbiscan Stability Index (TSI) is a parameter used to evaluate the stability of emulsions and suspensions, measured using the Turbiscan instrument. This device analyzes the transmission and scattering of light along the height of the sample, detecting changes in optical properties that indicate variations in particle concentration, droplet size, and structural alterations in the emulsion or suspension over time. Generally, low TSI values indicate more stable emulsions, while higher values suggest instability associated with phenomena such as flocculation, sedimentation, cream formation, and coalescence [76–78].

Figure 11 presents the TSI values for emulsions of WBPC, PPC, and SPI under different pH conditions (4 and 7) and oil-to-water ratios (1:1 and 2:1). Overall, emulsions at pH 7 exhibit greater stability, characterized by lower TSI values, which can be attributed to the higher net charge of the proteins in neutral pH, reducing aggregation due to electrostatic repulsion and being further from the isoelectric point. Conversely, at pH 4, near the isoelectric point of the proteins, the emulsions show a tendency toward aggregation and phase separation, resulting in higher TSI values and indicating lower stability.

Among the proteins, the emulsions containing pea protein (represented by blue stars in the 2:1 water/oil ratio at pH 7) and white bean protein (represented by black squares and red circles) display the lowest TSI values, indicating these emulsions are more stable compared to those with soy protein and pea protein, showing less variation over time. The emulsions of soy and pea proteins at pH 4 in both oil/water ratios exhibit an increase in TSI over time, with higher values indicating instability, possibly due to sedimentation or phase separation. This suggests that these proteins exhibit lower stabilization capacity in emulsions under these conditions compared to white bean protein.

The greater stability observed for emulsions with white bean protein can be explained by its higher oil retention capacity (HOC) and predominant β-sheet secondary structure, which appears to possess a more flexible structure, allowing for more efficient interaction at the oil–water interface. This characteristic makes white bean protein a promising alternative for food applications requiring stable emulsions. Additionally, another factor potentially contributing to the lower TSI values for white bean protein emulsions is their superior viscosity, which may enhance their physical stability by reducing the particle mobility and consequently the frequency of collisions between them, thereby promoting stability [15].

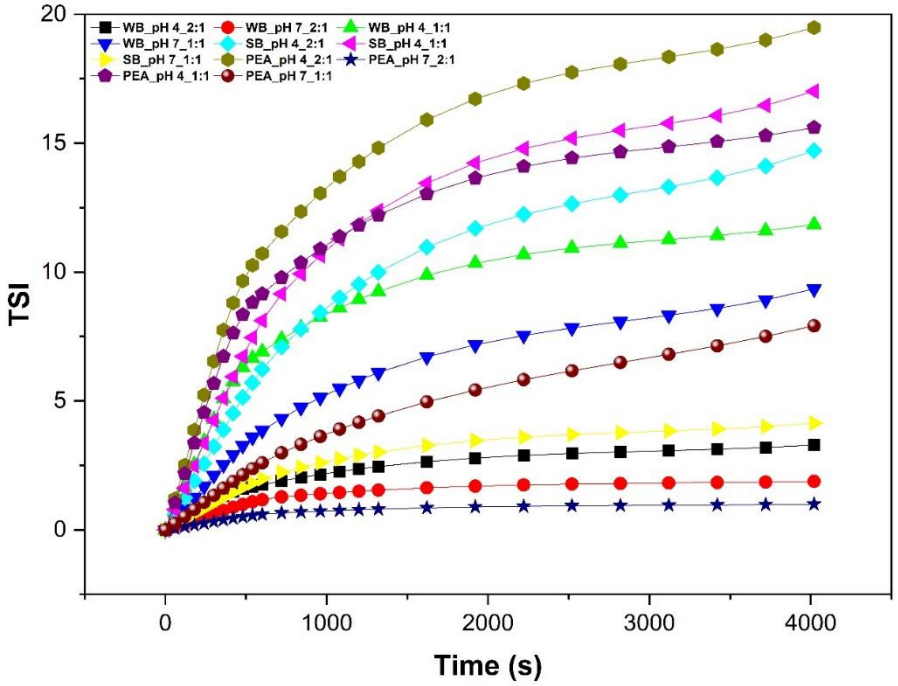

Figure 11. Turbiscan Stability Index (TSI) as a function of time (seconds) for emulsions formulated with white bean (WB), soy (SB), and pea (PEA) proteins at different pH values and oil/water ratios. The samples were evaluated at pH 4 and pH 7, with oil/water ratios of 2:1 and 1:1. The symbols represent the different treatments. The evolution of the TSI values reflects the stability of the emulsions, with lower values indicating greater stability.

4. Conclusions

The results of this study suggest that white bean protein concentrate (WBPC) exhibits unique and promising functional properties for application in the food industry. Compared to soy protein isolate (SPI) and pea protein concentrate (PPC), the WBPC demonstrated distinct characteristics in its secondary structure, including a higher proportion of β-sheets and a more flexible conformation, which may facilitate interactions with different molecules. The rheology analysis of the WBPC indicated a rigid gel structure at high protein concentrations (above 20%), showcasing its potential for use in formulations requiring high mechanical strength and elasticity.

In the emulsion stability analysis, the WBPC showed a competitive stability index (TSI), especially at neutral pH, where it was able to form more stable emulsions compared to the pea and soy concentrates. This indicates good oil retention capacity (OHC) and resistance to phase separation. These results may be attributed to WBPC's hydrophobic structure and high oil-holding capacity, factors that contribute to effective diffusion at the oil–water interface, making it a valuable option for emulsified systems, such as meat products and protein-based beverages.

Although the WBPC exhibited lower surface hydrophobicity and water-holding capacity (WHC) compared to soy and pea proteins, its high OHC suggests it is suitable for fat-rich products that require emulsification and long-term stability. The lower hydrophobicity may further confer WBPC greater flexibility for structural changes, favoring solubility and interaction with polar compounds, which broadens its application potential across various food systems.

Overall, this study highlights WBPC as a competitive alternative to traditional plant proteins, with characteristics that could be leveraged to develop innovative and stable food products in the industry. However, future research is required to optimize its solubility and explore structural modification techniques that could further enhance its functional properties and applications.

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GENERAL CONCLUSION

Common white bean (*Phaseolus vulgaris* L.) stands out as a legume with high nutritional value and promising technological potential, particularly in light of the growing demand for plant-based ingredients. Its composition, marked by a high protein content, carbohydrates, and dietary fiber, combined with its technofunctional properties, makes it a versatile candidate for incorporation into innovative food formulations. However, the proteins extracted from this legume remain understudied, especially regarding a detailed characterization of their physicochemical and functional properties. This knowledge gap limits their effective utilization in the food industry and underscores the need for more in-depth investigations to enable their practical application in various food systems.

The results obtained in this study reinforce the potential of legumes, particularly white bean, as an alternative source of plant protein with attractive technological attributes for use in the food industry. The proteins extracted from this legume exhibited superior functional performance compared to widely used plant proteins, such as soy and pea, especially in systems requiring emulsification and foam formation. Notably, the emulsions demonstrated high stability at neutral pH, a remarkable oil-holding capacity, and the ability to form rigid gels at high protein concentrations, desirable traits for complex food formulations. The higher proportion of β-sheet structures in the protein concentrate's secondary structure may be associated with greater affinity for nonpolar regions, while the less ordered conformation could enhance interactions with various compounds and interfaces, broadening the range of possible applications for this protein in diverse food systems.

Although certain limitations are associated with the native structure of white bean proteins, such as low solubility at acidic pH and limited gelling capacity at lower concentrations, these constraints are not exclusive to this matrix and can be overcome. The application of emerging technologies, including ohmic heating, ultrasound, and pulsed electric fields, as well as the controlled addition of ions, has proven effective in inducing structural modifications in plant proteins, resulting in improved technofunctional properties. Enhancing these characteristics may enable the use of white bean proteins in a broader spectrum of food products.

The incorporation of white bean protein contributes to the diversification of available protein sources for the development of products targeted toward vegan, vegetarian, and flexitarian consumers, offering sustainable alternatives. In addition to its technological potential, increasing the value of this legume could encourage greater domestic production in

Brazil, currently limited, thereby improving its availability and accessibility in the national market. In this context, the present study provides a scientific foundation regarding the composition, technofunctional properties, and potential applications of white bean protein concentrate, serving as a reference for future research and innovation strategies. Investments aimed at optimizing extraction methods, applying functional modification techniques, and validating the use of these proteins in different food matrices are essential to establish their use at an industrial scale and to strengthen more sustainable, safe, and economically viable value chains.