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Lupin as an Alternative Source of Protein for Plant-Based Foods—A Review

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ABSTRACT

Lupin, an underutilized legume belonging to the Fabaceae family, demonstrates a huge potential as an alternative protein source by contributing to food security and environmental resilience in the face of climate change. This work highlights the potential of lupin protein as a preferred substitute for soy protein in plant-based food applications. A critical assessment of the protein extraction methods for lupin and their influence on the physicochemical and nutritional properties of the extracted lupin protein was determined. Furthermore, the structural and physicochemical properties of lupin proteins compared to those of soybean were examined. Despite its high protein content and excellent amino acid profile, the poor functional properties of lupin protein in comparison to soy posed a major limitation for its use in food formulations. Based on this observation, the effect of novel and non-thermal processing on lupin protein was further determined. Findings revealed increasing utilization of lupin protein for novel foods, but limited success in the adoption of lupin protein in the mainstream plant protein sector, attributed largely to the presence of anti-nutritional factors, allergens, and inferior organoleptic qualities. Therefore, by offering process-induced improvement of the functional properties, a wider application of lupin protein in food products could address the protein diversity challenge.

1 | Introduction

Proteins are essential macronutrients that are required for human growth and development. The global landscape of protein supply is dominated by vegetal sources (~60%) and others from animal-derived sources; nevertheless, their contribution to the overall protein intake at the population level differs across geographies (Smith et al. 2024). Global food insecurity signifies an urgency to fix the environmental impact of the current food system in which animal protein production alone is responsible for 14.5% of the total food-related greenhouse gas (GHG) emissions and contributes to 30% biodiversity loss (Crippa et al. 2021; Duluins and Baret 2024). Interestingly, beef and dairy products account for 65% of the total global emissions from animal husbandry, where major attributes are feed production, processing, and digestion by cows (Vellinga and de Vries 2018; von Greyerz et al. 2023). Thus, with the increasing world population, the demand for dietary proteins from animal sources is no longer sustainable. There is a need for a paradigm shift that will result in a rebalancing of consumption of proteins of animal origin by increasing proteins from alternative and underutilized plant-based sources such as lupin. Although disadvantaged due to its functional property limitations, lupin, with its high protein and fiber content of about 40% dry weight, is currently explored as a potential plant protein substitute (Arnoldi et al. 2015; Lo et al. 2024).

The increasing consumption of plant proteins has proven to be one of the solutions for mitigating the emission impact of livestock farming (Ahmad et al. 2022). The global plant protein

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market in 2022 was estimated to be USD 13.27 billion and is expected to grow to approximately USD 25.53 billion by 2030 (Anyiam et al. 2025). One of the commonly used proteins from plant origin is soy, however, there is currently an over-dependence on soy protein within the plant-based food market which has also impacted biodiversity (Munialo et al. 2025). Furthermore, soy protein production, particularly in South America, has been shown to be a significant driver of deforestation, especially in the Amazon rainforest, in addition to the pressure resulting from the competition of its use as both animal feed and human food (Amaral et al. 2021; Munialo and Vriesekoop 2023). Thus, diversification of plant protein usage beyond soy by introducing some of the under-utilized sources such as lupin for food applications is of paramount importance. However, this requires further understanding and possible modification of the functional properties of lupin and other under-utilized plant proteins as well as assessing their upscaling opportunities (Sim et al. 2021; Nikbakht Nasrabadi et al. 2020). This work therefore explores the utilization of lupin protein as a sustainable and alternative plant protein source. Lupin protein characteristics, extraction methods, techno-functional properties and use in different food applications when compared to soy protein is further discussed in this work.

2 | Lupin as a Sustainable Protein Source

Lupin is a legume belonging to the Fabaceae family and consists of four major species—*Lupinus albus* L. (white lupin), *Lupinus angustifolius* L. (narrow-leafed or blue lupin), *Lupinus luteus* L. (yellow or sweet lupin), and *Lupinus mutabilis* (Andean lupin) (Bader et al. 2009; Gresta et al. 2017). The global production of lupin is estimated around 1.01 MT with Australia, Russia, and Poland as the main producers as opposed to soy, which has a total production of 340 MT that corresponds with a total growth area of 123 million hectares (Shrestha et al. 2021). Over 80% of soy produced globally originates from the United States, Brazil, and Argentina combined, which are also the largest countries that export soy (Dreoni et al. 2022). Although the global production of lupin is way less compared to soy, an increase in its usage and demand could necessitate an increased cultivation and subsequent use in food production and processing (Figure 1). Currently, only 4% of the total lupin production is used for human consumption and the others are used as animal feed (Abraham et al. 2019). Australia is one of the biggest growers of lupin and is responsible for 80%–85% of world production, whereas the European Union (EU) and the United Kingdom (UK) hold 17.6% of the total production (Lo et al. 2021). However, the EU and UK can potentially expand their production if the extraction of protein fractions that pose exceptional techno-functional characteristics remains viable. This will reduce the over-reliance on imported soybean as the main plant protein source in the UK and the EU.

Aside from being a good protein source, other advantages derived from lupin cultivation include: (i) higher nitrogen fixation rate than other legumes (150–200 kg N_2/ha) and positive impact on mobilizing soil-bound phosphate; (ii) low production cost; (iii) cultivation under stress conditions, therefore more adaptable under climate change conditions; and (iv) lack of genetic modification in the commercial cultivation, unlike soy (Shrestha et al. 2021). Additionally, environmental adaptations and quality attributes (especially low alkaloid content) can be selected or developed in the gene pool to address the technological challenges for the cultivation of high-quality lupin. Overall, lupin could be the future protein crop for Europe (Lucas et al. 2015) and in regions where cultivated.

3 | Lupin Protein Characteristics

Lupin has substantial protein content of 30%–42% in the seed depending on the variety, and 40% in dehulled kernels which is

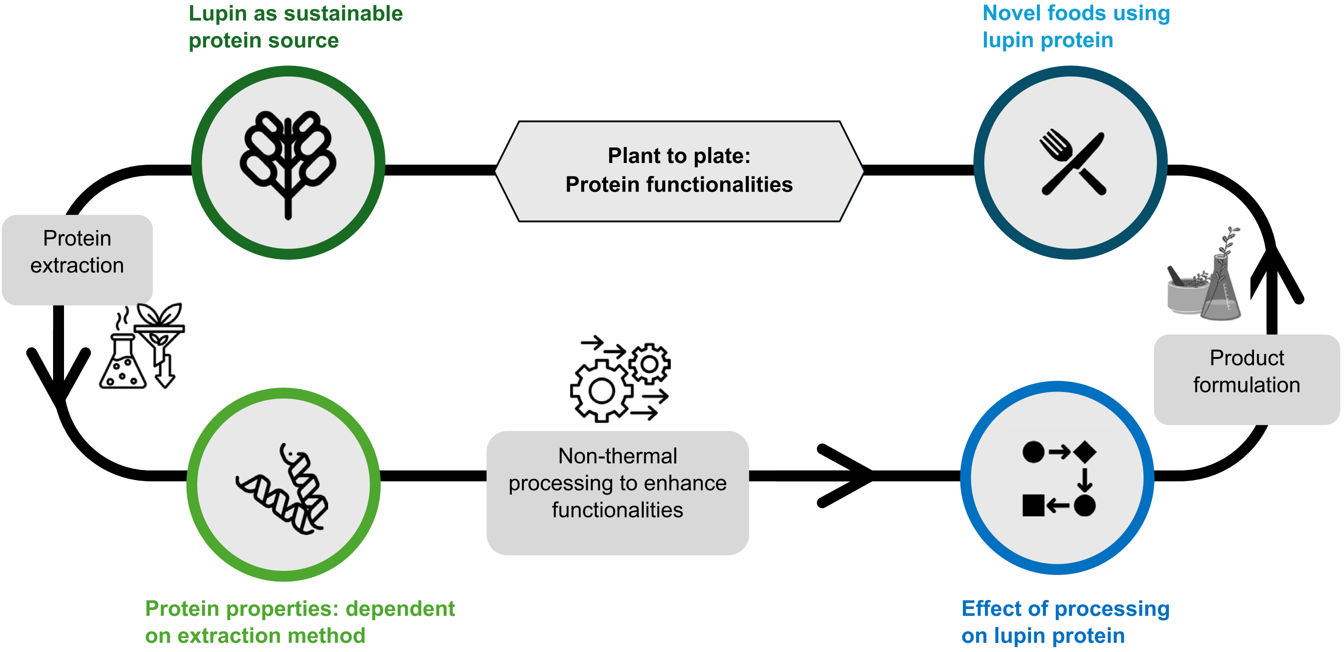

FIGURE 1 | Lupin as a sustainable protein source and soy replacement in food processing.

TABLE 1 | Comparative characteristics of lupin and soybean protein.

Protein characteristic	Soybean	Lupin	References
Protein structure	Complex globular	Globular	Shrestha et al. (2021), Kim et al. (2020)
Protein content	40%	30%–55%	Lo et al. (2021), Vogelsang-O'Dwyer et al. (2022)
Protein fractions	β-conglycinin (7S) Glycinin (11S) Globulin (15S)	β-conglutin (7S) α-conglutin (11S) γ-conglutin (2S)	Nikbakht Nasrabadi et al. (2020), Lo et al. (2021)
Isoelectric point	4.6	4.5	Lo et al. (2021), Kim et al. (2020)
Denaturation temperature	78.6°C–90.8°C	63°C–74°C	Lo et al. (2021)
Water holding capacity	6.13 g/g	1.71 g/g	Lo et al. (2021), Tan et al. (2014)
Oil holding capacity	1.51 ± 0.04 g/g	1.43 g/g	Tan et al. (2014)
Emulsifying activity	47.4% ± 2.30%	61.94%	Lo et al. (2021), Tan et al. (2014)
Emulsion stability	100% ± 5.5%	90%	Lo et al. (2021), Tan et al. (2014)
Least gelling concentration	12%	7%	Tan et al. (2014)
Molecular weight	150–200 kDa	20–100 kDa	Kim et al. (2020)
Digestibility	85.2%	90%	Tan et al. (2014), Bartkiene et al. (2018)
Zeta potential	−30 mV	−35 mV	Lo et al. (2021)
Solubility	67.34% (pH = 12)	64%–90% (pH = 8)	Tan et al. (2014), Lo et al. (2022)

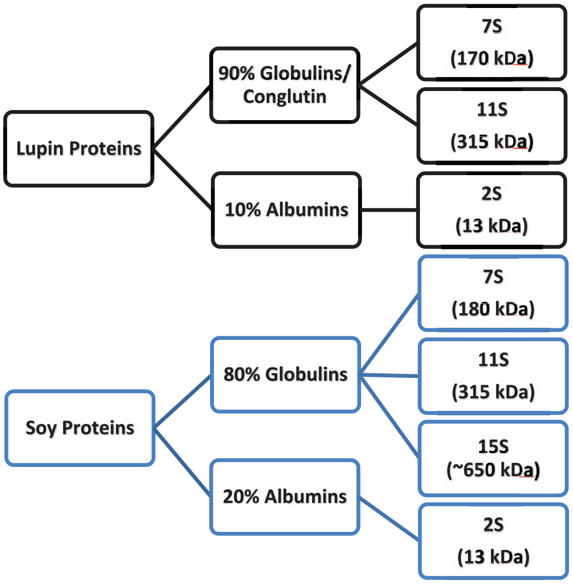

FIGURE 2 | Comparison of the molecular weight distribution of various subunits present in lupin and soy proteins.

very similar to the protein content of soybean (~40%) (Monteiro et al. 2014). Compared to soybean, lupin has low carbohydrate and fat content as well as a higher dietary fiber content (~28%) (Bähr et al. 2014). Table 1 highlights the physicochemical properties of lupin and soybean proteins describing their functional similarities and differences which could help to assess the potential of lupin protein to substitute soy protein for the plant-based food formulation.

Lupin protein comprises albumins, globulins and prolamins, with albumin and globulins occurring in the ratio of 1:9, while prolamins occur in minor fractions (Boukid and Pasqualone 2021). Globulins, which are lupin's major storage proteins, are high molecular weight and consist majorly of 7S β-conglutin, which comprises a trimeric structure with 15 subunits of 20–60 kDa each, forming a 170 kDa complex; and 11S α-conglutin comprising a hexameric structure with both acidic and basic chains and a MW of 315 kDa, all constituting 80%–90% total protein. The minor 7S γ-conglutin (monomeric unit with a MW of 17 kDa, containing one large and small subunits) and 2S δ-conglutin (tertiary structure with a MW of 48 kDa) (Figure 2). A breakdown of the composition of globulins based on their electrophoretic mobility includes α-conglutin (35%–37%), β-conglutin (44%–45%), γ-conglutin (4%–5%), and δ-conglutin (10%–12%) (Arnoldi et al. 2015; Boukid and Pasqualone 2021). Structurally, lupin seed proteins consist of fractions of glycosylated storage proteins including α- and β-conglutins and, to a lesser degree, γ- and δ-conglutins (Faeste 2010; Boukid and Pasqualone 2021). The α-conglutin from the 11S globulin family and the β-conglutin from the vicilin-like 7S family consist of two cupin domains: a large and functionally vast family of proteins. Faeste (2010) further revealed that α-conglutin occurs in *L. albus* as a hexamer of disulfide-linked basic and glycosylated acidic trimers, having a molecular weight of 47–54 kDa and linked to a basic polypeptide of approximately 20 kDa. However, β-conglutin is a non-covalently linked heterogenous trimer comprising polypeptides of between 20 and 80 kDa. The γ-conglutin is a basic protein with homogenous tetramers comprising two different disulfide-linked monomers of 17 and 30 kDa, with the 30 kDa monomer existing as the glycosylated form (Faeste 2010). Conversely, δ-conglutin is a 2S albumin of 14 kDa comprising two disulfide-linked proteins of 4 and 9 kDa possessing a cysteine-rich prolamin formation. Comparatively, soybean protein has a complex globular structure, and approximately 90% is composed of β-conglycinin (7S) and glycinin (11S). β-conglycinin usually has a molecular weight in the range of 150–200 kDa and is a trimeric protein consisting of three subunits α (68 kDa), ά (72 kDa), and β (52 kDa) forms in which β subunits contain only core regions while α and ά units have extended regions of N-terminal sites. The 11S glycinin has a MW of 300–380 kDa, consisting of acidic and basic polypeptides with six subunits (hexamer) linked with disulphide bonds and overlapped hexagon shape to form a void cylindrical shape. The shape is maintained by hydrogen and/or electrostatic bonding and hydrophobic interaction holding the structure (Kim et al. 2020).

Lupin shows low solubility around the pH equivalent to the isoelectric point (pI) of protein due to aggregation. The pI for both lupin and soy proteins is at a pH range of between 4 and 5, however, soy protein has a higher denaturation temperature (T_d) compared to lupin protein, depicting superior thermal stability. Furthermore, the oil holding capacity for lupin protein is slightly lower than soy protein while the water holding capacity of lupin protein is almost four times lower than that of soy protein. Differences in the water holding capacity could be attributed to the type of network that these proteins form in the presence or absence of other gelling agents. The networks made from soy could have a higher ability to imbibe and hold on to more water, thus making soy proteins the preferred protein for applications that require good water holding capacity such as in the formulation of meat analogues. However, lupin protein can be used in applications that require good ability to stabilize water–oil interfaces as good emulsifiers. The foaming capacity of protein is the amount of interfacial area created by whipped protein. Both lupin and soy have a similar range of foaming capacity of 70%–90% and 70%–80%, respectively which varies depending on the source and treatment conditions. The foaming capacity of lupin enables it to be used as a substitute for soy in food formulations that require a consideration of foaming ability and stability.

Lo et al. (2021) demonstrated that the zeta potential for lupin protein showed a positive value at the acidic pH and a negative value for the alkaline environment, with a value of −10 mV near pI. Despite having more disulfide bonds and free thiol groups, lupin protein showed poor gelling properties with weaker, non-elastic, and deformable gel formation compared to soy protein, which forms tough, firm, and resilient gel (Berghout, Boom, and van der Goot 2015). This was attributed to the hindered unfolding of lupin protein preventing the formation of gel network due to the lack of accessibility of disulfide and free thiol groups, which in turn could result in lower water holding capacity (Lo et al. 2021). The presence of hydrophobic amino acids on the protein surface plays a crucial role in the absorption of protein at the oil–water interface during emulsion formation (Wang et al. 2022). Lo et al. (2021) and Tan et al. (2014) showed that the emulsifying activity index (EAI) of soy protein isolate (SPI) is similar to that of lupin protein isolate (LPI), but the emulsifying stability index (ESI) of SPI was found to be higher than that of LPI (Table 1). This suggests that both SPI and LPI have similar emulsion formation capacity, but SPI can stabilize the emulsions for a longer period than LPI.

4 | Extraction of Lupin Protein

The extraction of high quality protein from lupin seeds facilitate the development of diversified plant protein ingredients. Recent studies have focused on optimizing the extraction process for increasing the protein yield and improved functionalities with minimum environmental impact (Table 2). It has been observed that the protein recovery rates vary considerably (23%–90%) across different extraction techniques including extraction based on novel technologies (Rababah et al. 2023; Chukwuejim et al. 2024; Dominguez-Valencia et al. 2025; Tang et al. 2025). Lupin protein recovery was shown to be linked with the pretreatment for de-fatting and the highest recovery occurred using diethyl-ether to separate the fat before isolating protein (Bader, Bez, and Eisner 2011; Bader, Oviedo, et al. 2011).

4.1 | Lupin Protein Extraction Methods

Alkaline extraction in combination with ultrafiltration or isoelectric precipitation, remains the predominant method for isolating both albumin and globulin fractions of lupin protein (Aguilera et al. 1983; Lam et al. 2018; Domínguez et al. 2023). The underlying principle is to leverage pH-dependent solubility of lupin protein which is driven by the inter-play between protein–protein and protein-water interactions. Earlier works on alkaline extraction of lupin protein reported high yield (Chew et al. 2003), but recent attempts achieved lower protein recovery, highlighting methodological inconsistencies (Albe-Slabi et al. 2022; Lo et al. 2022). However, the application of ultrasound (US) pretreatment in combination with alkaline extraction, reported increased yield of lupin protein (Aguilar-Acosta et al. 2020; Navarro-Vozmediano et al. 2025). Factors such as post-extraction drying (freeze-, spray-, or vacuum drying) step critically impacts lupin protein functionality; freeze-drying without excipients may reduce solubility via protein aggregation (Munialo et al. 2022; Domínguez et al. 2023). Micellization, or salt extraction offers a milder process by solubilizing globulin proteins in NaCl or KCl at neutral pH and salting-in at low temperature (1°C–4°C) thereby avoiding denaturation (Fontanari et al. 2012; Lam et al. 2018). On the other hand, acid extraction utilizes pH shift in combination with ultrafiltration, to selectively extract acid-soluble fraction of lupin γ-conglutin thereby achieving 84%–90% yield (Shrestha et al. 2021). However, this method resulted in lower extraction yield and compromises color parameters in other plant proteins (Wang and Xiong 2019), thus necessitating further evaluation for lupin-specific application.

While the wet process achieves purity in protein extraction, the major drawbacks are water and/or organic solvent usage as well as the requirement of an energy intensive de-watering step which can be circumvented by using novel extraction technology such as dry fractionation (Pelgrom et al. 2014; Chukwuejim et al. 2024). The protein yield and purity in dry fractionation depend on the degree of milling and the air flow rate. A study conducted by Politiek et al. (2023) showed that the presence of ~8% oil bodies did not impede the dry fractionation of lupin flour and provided 54%–59% protein yield. Importantly, defatting lupin flour prior to dry fractionation results in changed solubility and flavor profiles in the extracted protein, suggesting that oil removal strategies require careful optimization. During wet

TABLE 2 | Summary of different protein extraction methods applied to lupin.

Extraction method	Protein fractions	Protein content (%)	Extraction yield (%)	Processing conditions	Key advantages	Major limitations	References
Alkaline extraction + IEP	Globulins (α-, β-conglutin)	87.7–96.8	23–59	pH 8.5–12, pH 4.5 precipitation	High purity, established process	Protein denaturation risk, water intensive	Chukwuejim et al. (2024), Shrestha et al. (2021)
Alkaline extraction + ultrafiltration	Albumins + globulins	89	69–82	pH 8.5–12, membrane filtration	Dual fraction recovery	Complex equipment, high energy	Chew et al. (2003)
US + alkaline extraction + IEP	Mixed fractions	28–47	ND	85 W/cm^2 acoustic power, alkaline pH 8, acid precipitation pH 4.5	Distinct protein extraction performance with US assistance.	Process optimization required	Aguilar-Acosta et al. (2020)
Micellization/salt extraction	Globulins	75–85	19.8–30	15°C–35°C, use salt solutions, 1°C–4°C for precipitation	Mild conditions, less denaturation, high solubility	Lower yields, salt waste	Lam et al. (2018), Fontanari et al. (2012)
Acid extraction + ultrafiltration	γ-conglutin (selective)	84–90	37	pH < 4, ultrafiltration	Selective fractionation	Color deterioration, limited scope	Shrestha et al. (2021), Wang and Xiong (2019)
Dry fractionation	Albumins + globulins	54–59	13	Mechanical milling, air classification	No solvents, energy efficient	Lower purity, oil interference	Chukwuejim et al. (2024), Pelgrom et al. (2014), Politiek et al. (2023)
Supercritical CO_2	Mixed fractions	93.8	57	400 bar, 93 min, 4 kg/h flow	High purity, low oil content	High capital cost, complex operation	Dominguez-Valencia et al. (2025)
Combined US-MW assisted	Mixed fractions	76–86	44–57	10 min, optimized power settings	Rapid processing, synergistic effects of US and MW	Equipment complexity, power optimization needed	Tang et al. (2025)
HPU + alkaline extraction	Enhanced mixed fractions	Enhanced	+15 improvement	3–9 min pretreatment + conventional	ANF reduction, improved functionality	Multi-step process, optimization required	Navarro-Vozmediano et al. (2025)

Abbreviations: ANF, anti-nutritional factor; HPU, high-power ultrasound; IEP, isoelectric precipitation; MW, microwave; ND, not determined; US, ultrasound.

extraction, the alkaline solubilization step incorporates oil and other lipophilic compounds into the LPI to decrease the overall extraction yield, while the defatting procedure using hexane can lead to decreased protein solubility and off-flavor. Thus, to address the limitations of solvent-based extractions, supercritical carbon dioxide (SC-CO_2) extraction emerged as a promising alternative which showed improved protein purity, higher extraction yield, and reduced oil content in the LPI (Dominguez-Valencia et al. 2025).

Tang et al. (2025) opined that by synergistically leveraging the cavitation effects of US with the rapid, uniform heating capabilities of microwave (MW), a combined technique of 10 min processing could achieve enhanced extraction efficacy of lupin protein, thereby outperforming the time-consuming conventional extraction methods. It was further suggested that lower power combinations of US and MW effectively improved solubility of extracted lupin protein and reduced particle size, while higher power combinations resulted in decreased solubility due to protein denaturation and aggregate formation. Navarro-Vozmediano et al. (2025) who explored high-power ultrasound (HPU) pretreatment as a method for reducing anti-nutritional factors (ANF) and fat content while enhancing protein extraction efficiency, observed that the HPU pretreatment enhanced critical functional properties including water absorption index (26% improvement), foaming capacity (8% enhancement), and emulsifying properties (14% improvement).

4.2 | Techno-Functional Properties of Lupin Protein Extracts

Lupin protein techno-functional properties are significantly influenced by the extraction process (Table 3). Observed variation stems from the structural modification of extracted lupin protein which imparts different surface hydrophobicity, denaturation and particle size. Previous studies revealed that alkaline extraction–isoelectric precipitation achieves approximately 59% protein recovery in lupin kernel, which can be further improved to 69%–82% when coupled with diafiltration/ultrafiltration or three-phase centrifugation, with high purity of up to 91% from the de-oiled extract (Aguilera et al. 1983; Chew et al. 2003). However, later studies have failed to reproduce such high yield extraction and reported an extraction yield of protein from lupin flour in the range of 2%–36.4% dry weight with varied purity level (D'Agostina et al. 2006; Alu'datt et al. 2017; Domínguez et al. 2023). This could be attributed to the method of protein characterization and types of lupin varieties used in the extraction process. It was observed that acidic extraction of 37% dry matter basis compares favorably with alkaline methods of 40%–45% yield, while salt-induced extraction results in low yield of 19.8%–30.0% dry matter (Sussmann et al. 2013; Albe-Slabi et al. 2022). However, the application of novel extraction technologies to lupin such as dry fractionation yields 54%–59% protein content (dry weight) with a 13% yield, while SC-CO_2 treatment as well as combined US and MW significantly improved the yield and protein content (Politiek et al. 2023; Dominguez-Valencia et al. 2025; Tang et al. 2025).

Alkaline extraction with isoelectric precipitation yield globulins, while ultrafiltration retains albumin (Shrestha et al. 2021; Albe-Slabi et al. 2022). Although globulin is receiving more interest in plant protein isolates than albumins, albumins possess better foaming capacity owing to their less aggregated state and smaller size (Yang and Sagis 2021). Kohajdová et al. (2011) showed that lupin foam was quite similar in microstructure and texture when compared to the uncooked egg white foam, thus underscoring the importance of retaining albumins in LPI especially when exploring plant-based eggs. Lima-Cabello et al. (2016) observed that γ-conglutin, a minor globulin protein fraction (~4%–5% w/w) in lupin, has shown promise for controlling blood glucose levels needed to reduce the risk for type II diabetes. Unlike α- and β-conglutin fractions of lupin, γ-conglutin is acid soluble with a pH of 7.9–8.2, heat stable, and exhibits unique emulsifying properties. However, yield, purity, and scalability of extraction are still major challenges to overcome in the extraction of γ-conglutin lupin fraction (Mane et al. 2018). Lupin conglutin (α-, β-, γ-) are potential allergens with cross-reactivity to peanuts (Lucas et al. 2015). While supercritical fluid extraction and acidic extraction alter protein secondary structures, their impact on allergenicity is unknown (Albe-Slabi et al. 2022; Tang et al. 2025).

Solubility and foaming are important physicochemical properties as many food product formulations involve dispersion and emulsion. Alkaline extraction of lupin protein using isoelectric precipitation demonstrated low foaming capacity whereas ultrafiltration and dry fractionation resulted in extracts with high foaming capacity (Wong et al. 2013; Pelgrom et al. 2014). Micellization showed improved characteristics in lupin protein solubility when compared to alkaline extraction and this has been attributed to pH and ionic strength (Shrestha et al. 2021). Politiek et al. (2023) stated that micellization and SC-CO_2 de-oiling improve foaming by reducing protein aggregation and optimizing air-water interface affinity. The foaming stability of lupin protein is similar to chickpea protein but inferior to broad bean (Alu'datt et al. 2017), whereas the foaming capacity is dependent on the extraction method (Lo et al. 2021), pH (Rodríguez-Ambriz et al. 2005), and the lupin variety (El-Adawy et al. 2001).

5 | Lupin Protein Modification Using Non-Thermal Techniques

High-pressure homogenization (HPH) and US treatments are emerging as non-thermal process technologies used in altering the functional properties of plant protein. Lupin protein modification using sustainable processing methods can be harnessed to improve its techno-functional properties, thereby overcoming the current limitation of lupin protein usage as a food ingredient.

5.1 | High-Pressure Homogenization

HPH has shown to modify the structure and functionality of lupin protein by generating short-duration dynamic pressure (~10^{-4} s) combined with cavitation, shear stress, and turbulence which cause particle size reduction and induce conformational changes through protein unfolding (Lo et al. 2024). In the study conducted by Lo et al. (2024), application of HPH within low pressure range of 25–100 MPa at pH 5 and 9 was

TABLE 3 | Techno-functional properties of lupin protein.

Extraction method	Solubility	Emulsification properties	WHC (mL/g)	OHC (mL/g)	Foaming Capacity	Thermal stability	References
Alkaline extraction + IEP	Lower solubility at neutral pH (~10%–50% at pH 6–7)	EC: 42%–43%; stable emulsions	1.7	1.7	Low (pH-dependent)	Moderate denaturation	Albe-Slabi et al. (2022), Rodríguez-Ambriz et al. (2005)
Alkaline extraction + ultrafiltration	Improved solubility at pH 7	EC: 42%–43%; stable emulsions	1.3–1.7	2.2–2.8	High (212%–242%)	High thermal stability	Albe-Slabi et al. (2022), Tadesse (2021), Berghout, Boom, and van der Goot (2015), Berghout, Pelgrom, et al. (2015)
Micellization	Higher solubility (~90% at neutral pH)	EC: 32.6%–43%; pH-dependent	1.3	2.2	Superior to IEP	Preserves native structure	Shenghua et al. (2021), Albe-Slabi et al. (2022), Rodríguez-Ambriz et al. (2005), Tang et al. (2025)
Dry fractionation	Moderate solubility	Limited data	2.2	2.9	Improved after de-oiling	Not reported	Tadesse (2021), Khalid and Elharadallou (2013)
Acidic extraction	Low solubility at pH 6–7 (10%–50%)	Similar to the alkaline methods	2.09	2.8	pH-dependent	Partial denaturation	Albe-Slabi et al. (2022), Shenghua et al. (2021), Khalid and Elharadallou (2013)
Supercritical-CO_2	Unaffected	Not reported	Not reported	Reduced oil content	Enhanced by de-oiling	Not reported	Dominguez-Valencia et al. (2025)
Combined US-MW assisted	Lower power: ↑ solubility; higher power: ↓ solubility	Not reported	Not reported	Not reported	Not reported	Alters secondary structure	Tang et al. (2025)

shown to reduce the particle size of lupin protein by up to 10-fold, but at higher pressures of 200 MPa, the particle size reduction was less pronounced. Chapleau and de Lamballerie-Anton (2003) who studied the aggregation properties of lupin protein due to high-pressure processing using 200–600 MPa at pH 7.0, observed a structural modification of the lupin protein at a pressure > 400 MPa via aggregation of 11S globulin fraction and denaturation of 7S globulin fraction. Such hydrophobic interactions due to exposed hydrophobic sites upon HPH resulted in increased protein interfacial concentration and therefore emulsion stability as well as decreased creaming index and flocculation because non-covalent interactions within protein aggregates are disrupted by HPH (Keuleyan et al. 2023).

Bader, Bez, and Eisner (2011) and Bader, Oviedo, et al. (2011) observed that the HPH dependent change in the functional property of lupin protein is linked to the lupin variety due to differences in protein fraction. There was no observed increase in the solubility of HPH treated *L. angustifolius*; however, *L. albus* showed a 5% increase in protein solubility upon HPH treatment and this was attributed to different dispersion behavior due to a range of particle aggregation. The emulsifying capacities (EC) of *L. angustifolius* and *L. albus* were not at all affected by HPH at a lower level of pressure (50–100 MPa), but there was a significant impact for *L. angustifolius* at the higher pressure (150 MPa) with enhanced EC due to the higher surface activity of protein, which improves the efficacy in the formation of interfacial layers (Bader, Bez, and Eisner 2011; Bader, Oviedo, et al. 2011). Additionally, the protein isolate of *L. albus* showed higher gel formation capacity compared to that of *L. angustifolius* upon high-pressure treatment, and the firmness and cohesion of gel using *L. albus* increased by a factor of four compared to the untreated samples.

Apart from particle size reduction, HPH was also shown to improve solubility and enhance viscosity and gelling properties of lupin protein when passed through multiple homogenization cycles (Lo et al. 2024). At 50 MPa, after 10 homogenization cycles, the particle size of lupin protein was reduced by ~89% and 91% at pH 5 and 9 respectively but was almost unchanged. Zeta potential indicates no significant alteration of surface charge of the protein particles as a function of HPH. The reduced particle size impacted the solubility of lupin protein, which was found to increase by 20%–40% particularly under lower pressures of 25–50 MPa at pH 5 and 9. However, prolonged homogenization at higher pressures of 100–200 MPa led to a decrease in solubility due to protein re-aggregation via enhanced hydrophobic interactions and disulfide bond induced protein–protein cross-linking. Viscoelastic properties of lupin protein upon HPH treatment at both pH 5 and 9 were observed and supported by enhanced loss modulus, with highest viscosity of ~100 Pa.s achieved at 200 MPa after 10 passes (Lo et al. 2024).

5.2 | Ultrasonication

Ultrasonication is another non-thermal technique which can be used in functional modification of plant proteins using low frequency (16–100 KHz) and high intensity (10–1000 W/cm^2) mechanical waves, thereby creating a high energy cavitation zone impact which changes the protein microstructure in the solution. Lo et al. (2021) reported that low-frequency US treatment of LPIs which demonstrated higher solubility and enhanced gelling properties in alkaline pH. Cavitation generated from US disrupts lupin protein aggregates and breaks non-covalent interactions thereby altering secondary structure which increases the random coil and facilitates improved water interaction, thus enhancing solubility (Jadhav et al. 2024; Riquelme et al. 2025). However, with the extended US treatment of 15 min at pH 9, the particle size of LPI was further reduced to < 1 μm but there was no significant change in solubility (Lo et al. 2022). It was further observed that the difference in zeta potential between US treated and untreated lupin protein at pH 9 was not significant, implying no perceptible change in lupin's surface characteristics. Improved gelling properties have also been observed with US treated lupin. A fourier transform infrared spectroscopy analysis of US treated lupin revealed reductions in α-helix and β-sheet, indicating partial unfolding with the microstructure analysis showing approximately 80% reduction in size of the lupin protein aggregate (Riquelme et al. 2025).

6 | Lupin Protein and Food Product Quality

A right balance of the physicochemical properties, nutritional profile and improved organoleptic attributes could help food manufacturers to adequately replace animal protein for lupin protein-based food formulations. Thus, functional characterization of lupin protein is important not only for the quality assessment of ingredients but also for identifying the appropriate product application (Abreu et al. 2023).

6.1 | Protein Quality

Among legumes, lupin species are reported to contain one of the highest protein levels and a great amino acid profile, with its amino acid score comparable to that of soy and higher than that of faba beans and pea protein (Boukid and Pasqualone 2021). Lupin protein has a higher amount of lysine and leucine (particularly *L. mutabilis*), but is low in methionine and cysteine when compared to other legume species. Estimated values of indispensable amino acids such as threonine, valine, and tryptophan were seen to be lower than that of soy (Boukid and Pasqualone 2021). Monteiro et al. (2014) reported a deficiency of all indispensable amino acids, except tryptophan, in *L. albus* and *L. angustifolius*. However, *L. luteus* possesses the highest concentration of indispensable amino acids when compared to other lupines (Boukid and Pasqualone 2021). Lupin species do not meet the WHO/FAO/UNU requirements for threonine and valine, but tryptophan and lysine in *L. luteus* contain amounts that meet the FAO/WHO requirements. Largely, the total indispensable amino acids of lupin species are lower than the 36 g/16 gN requirements of FAO/WHO, estimated based on the nine indispensable amino acids (Boukid and Pasqualone 2021). The mean digestible indispensable amino acid score (DIAAS) for lupin protein has been shown to be 68, which is higher than proteins from rice (47), oat (57), and fava bean (55); and comparable to pea protein (70), but lower than soy protein (91) (Herreman et al. 2020). In vitro studies reveal that lupin protein digestibility ranges from 72% to 84%, influenced by factors such as extraction

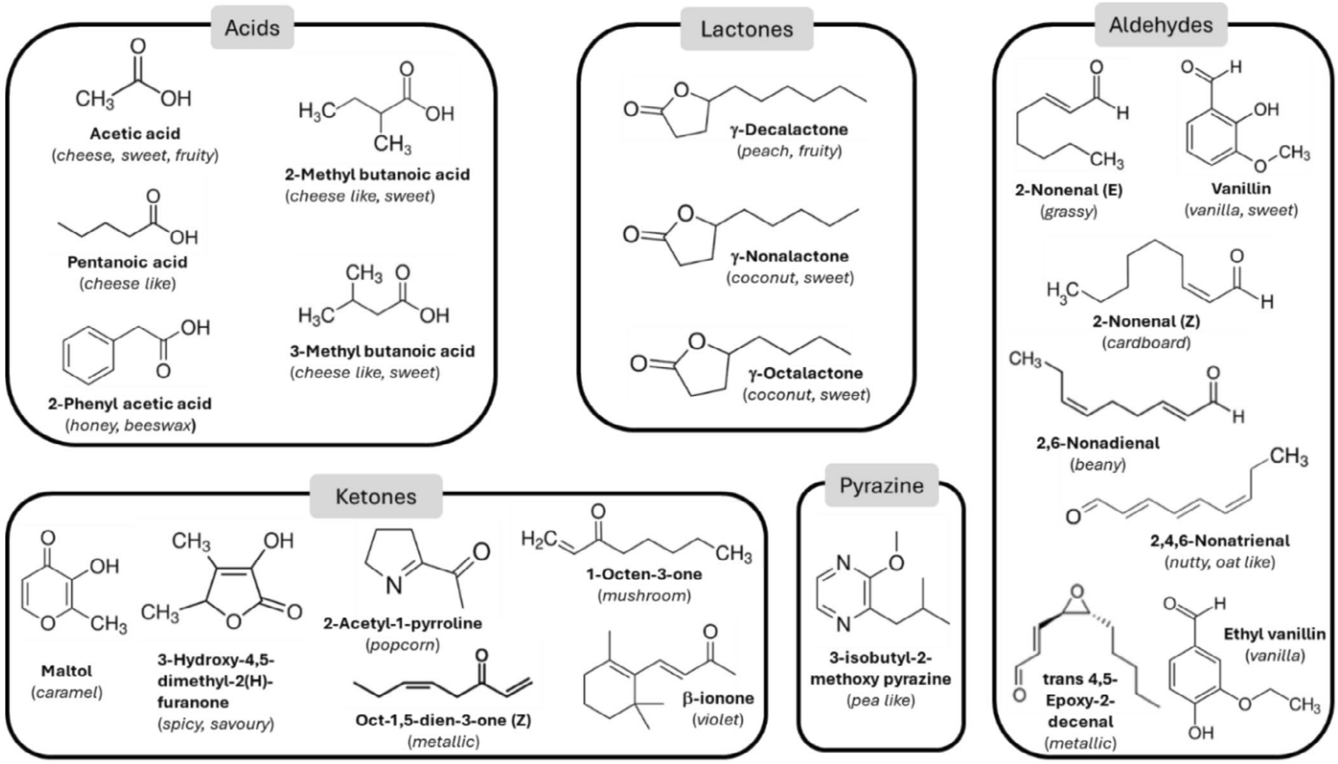

FIGURE 3 | Flavor volatiles and their aroma descriptors present in lupin. Adapted from Bader et al. (2009).

pH and thermal processing (Albe-Slabi et al. 2022; Chukwuejim and Aluko 2025). Lupin protein has also shown various health benefits, including reduction in blood glucose level and cholesterol, in addition to having a lower glycaemic index (Lucas et al. 2015). Due to the low level of ANF such as lectins and protease inhibitors, lupin protein has over 70% digestibility (David et al. 2024; Aghababaei et al. 2025).

6.2 | Flavor and Sensory Properties

Plant proteins are characterized by volatile compounds and off flavors which somewhat enhance or hinder their acceptability among consumers. A total of 26 aroma-active compounds has been reported for lupin flour (Bader et al. 2009) while 37 volatile compounds having 22 odorants were reported for lupin isolate (Schindler et al. 2011; Wanniarachchi et al. 2025). Among the odorants detected in lupin isolate are butan-2-one, heptan-1-ol, 4-methylpentan-2-ol, hexan-2-ol, 3-methylbutanal, octan-2-one, 3-methylbutan-2-ol, hexan-1-ol, and 2-methylpentan-2-ol, with most of these compounds either by-products of lipid oxidation or Strecker degradation of amino acids (Schindler et al. 2011; Wanniarachchi et al. 2025). Some of these volatiles and their aroma descriptors are summarized in Figure 3. Although the aroma profile of lupin flour of *L. angustifolius* was found to be characterized by grassy-green, fatty, and hay-like attributes, the LPI exhibited a very weak aroma profile with a slight hay-like odor (Bader et al. 2009). Furthermore, hexanal was reported to be responsible for the green and beany off-odor notes aroma in untreated LPI (Schindler et al. 2011). Aroma formation involves complex reactions, and the flavor release depends on the presence of other compounds within the matrix, and this can impact the flavor of the final product (Wang et al. 2025). For example, carbohydrate is known to influence flavor retention via formation of inclusion complex (Wang et al. 2022). Therefore, the starch content in LPI could play a role in flavor release during processing using methods such as High moisture extrusion (HME) which are commonly employed in the formulation of meat substitutes. When lupin is used in the fabrication of meat alternatives, the desired savory and meaty flavors can be achieved through the Maillard reaction (Chang et al. 2019). However, lower level of sulfur containing amino acids such as methionine and cysteine in lupin protein can potentially limit Maillard flavor formation.

Lupin protein faces the challenge of understanding how the composition of protein isolate drives the sensory characteristics as well as the effect of the lupin protein-based food matrix on the flavor release properties. The beany, off flavor of lupin protein is attributed to the conversion of polyunsaturated fatty acids to aldehydes and ketones (Bader et al. 2009). Chang et al. (2019) demonstrated that lipoxygenase-catalyzed oxidation is one of the major pathways for generating off flavors in plant proteins. Barallat-Pérez et al. (2024) showed in-mouth protein-aroma interaction for LPI and the highest lingering effect by volatiles like nonanal for perceived off-flavor intensity. Furthermore, alkaloids in lupin impart a bitter taste and the enzymatic hydrolysis of LPI, specifically the degradation of α- and β-conglutin by alcalase, has been shown to increase the bitterness (Schlegel, Sontheimer, et al. 2019). Pertaining to the off-flavor issues, thermal extrusion cooking is one of the most widely employed techniques for texturized plant proteins, which, besides creating the anisotropic fibrous meat-like structure, also enables the evaporation of off-flavor compounds and therefore improvement of the sensory appeal (Wang et al. 2022). Similarly, lactic acid fermentation has been shown to reduce the beany off-flavor in lupin protein extracts (Schlegel, Leidigkeit, et al. 2019; Wanniarachchi et al. 2025).

6.3 | Allergenicity

Despite its high protein content, the commercialization and acceptability of LPIs are impacted by the presence of allergens. Therefore, there is need for strategies to minimize or eliminate the risk of allergic reactions following the consumption of products made from lupin protein. Lupin is increasingly incorporated into plant-based foods, but its proteins can trigger IgE-mediated hypersensitivity that ranges from mild reactions to severe systemic anaphylaxis in sensitized individuals (European Food Safety Authority 2006; Czubinski et al. 2017; Hashemi et al. 2023). Lupin allergic reactions and sensitization prevalence globally is yet to be documented, but its prevalence in Europe is estimated to be around 0.3%–8% (Lima-Cabello et al. 2019; Boukid and Pasqualone 2021). Prevalence of lupin allergen varies depending on dietary habits and geographical regions (Verma et al. 2013; Faeste 2010; Villa et al. 2020). Gunal-Koroglu et al. (2025) revealed that allergies occur when the immune system misinterprets protein as harmful, thus triggering IgE-mediated reactions that extend from mild to severe. Protein structure, cross-reactivity, processing methods and gut microbiota have all been implicated as factors influencing allergenicity. Although physical, chemical and enzymatic processing techniques exert varying effects on the allergenicity of legumes, the path of exposure such as inhalation, skin contact or through the gastrointestinal tract, can influence allergenicity (Risha et al. 2024).

The molecular weight of protein binding IgE of lupin allergens is reported to be within the range of 13–66 kDa (Holden et al. 2008; Faeste 2010; Czubiński et al. 2016). The entire lupin conglutin subunits are considered as potential allergens and β-conglutin has been reported as the major allergen (Boukid and Pasqualone 2021). In relation to their structural characteristics, the presence of epitopes recognized by the immune system influences the allergenicity of proteins from alternative sources (Huang et al. 2024; Gunal-Koroglu et al. 2025). These epitopes occur as continuous or conformational amino acid sequences, with the continuous amino acid sequence epitopes retaining their allergen potency upon processing, while the conformational epitopes become susceptible to processing (Zhou et al. 2021; Geng et al. 2023; Gunal-Koroglu et al. 2025). Furthermore, proteins possessing tightly packed structures, disulfide bonds or glycosylation are more impervious to enzymatic hydrolysis, thereby increasing allergenicity (Gunal-Koroglu et al. 2025). Goggin et al. (2008) showed β–conglutin as the major lupin allergen (Lup-1), while Dooper et al. (2007), further reported α-conglutin (Lup-2) as highly allergenic with cross-reactivity activities. Currently, three allergens from different lupin species have been accepted by the World Health Organization/International Union of Immunological Societies (IUIS) (n.d.) Allergen Nomenclature Sub-Committee due to differences in protein content, composition and structure. The identified allergens include Lup an 1, a β–conglutin major allergen found in *L. angustifolius*, Lup an 3, a non-specific lipid transfer protein minor allergen found in *L. angustifolius* and Lup a 5, a profilin found in *L. albus* (Jappe et al. 2021; Risha et al. 2024). Other identified minor fractions as revealed from the Allergome database include the pathogenesis related-10 proteins Lup a 4 and Lup I 4 (Allergome 2023; Beyer et al. 2024).

Occurrence of allergic reactions has been reported upon inhaling and prolonged exposure to lupin seeds and products (Hashemi et al. 2023). Patients with peanut allergies have shown to be of higher risk to lupin allergy due to some cross-reactivity (Ballabio et al. 2010; Hashemi et al. 2023). Cross reactivity is known to occur in individuals with peanut sensitivity due to the presence of lupin α- and β-conglutin proteins implicated for allergic reactions in patients allergic to peanut (Czubinski et al. 2017). Furthermore, cross reactivity has been associated between lupin and other legumes because of the presence of identical epitopes within different proteins due to their three-dimensional or primary structure (Czubinski et al. 2017). Cross-reactions is seen to exist with proteins of molecular weights of 21, 35, 43–45, 55, and 65 kDa (Leduc et al. 2002; Czubinski et al. 2017). Cross-reactivity also occurs because lupin β-conglutin fraction demonstrates high sequence homology with the main peanut allergen *Ara h* 1 (Guarneri et al. 2005; Czubinski et al. 2017). Czubinski et al. (2017) described the symptoms of hypersensitivity to lupin proteins as urticaria, rhinitis, redness of mucous membranes, swelling of face, cough, breathing difficulty and systemic anaphylaxis in extreme cases. The dose range for these symptoms has been reported to be from 265 to 1000 mg of lupin proteins (Faeste 2010; Czubiński et al. 2016; Czubinski et al. 2017). Accordingly, the European Food Safety Authority recognized lupin as a food allergen in 2004, while in 2006, lupin and its products were included in European regulations (Directive 2006/142/EC) for its declaration in food labelling when used as a food ingredient (European Parliament and Council 2006; Faeste 2010; Boukid and Pasqualone 2021). In 2007, the EU Regulation No. 1169/2011 included lupin in 2007 among products leading to allergies and which must be declared on food labels (European Parliament and Council 2011; Boukid and Pasqualone 2021). Outside Europe, Australia and New Zealand have similarly regulated lupin as an allergen through the Food Standards Code, following a formal risk assessment and approval process (FSANZ 2017; Australian Government 2024).

Food processing methods including heat treatments as well as the effect of food matrix have been shown to affect lupin allergenicity differently (Aguilera 2019; Villa et al. 2020). Processing can enhance or mitigate allergen potency through modification of protein structures or by exposure of concealed epitopes (Dong et al. 2024; Gunal-Koroglu et al. 2025). It was observed that lupin proteins are stable during processing (Capraro et al. 2008; Jappe and Vieths 2010; Beyer et al. 2024). However, thermal processes such as baking, oven cooking and autoclaving were seen to mitigate the immunoreactivity of lupin proteins (Villa et al. 2020; Beyer et al. 2024). Thermal processing alters the integrity of the protein epitopes thereby affecting the immunoreactivity (Jiménez-Saiz et al. 2015; Bavaro et al. 2018; Hashemi et al. 2023). Aside the use of thermal treatments, other methods of mitigating the allergenic potential of lupin proteins is the use enzymatic hydrolysis. Schlegel, Sontheimer, et al. (2019) revealed that alcalase, papain and pepsin proteases were effective in degrading both α- and β-conglutin. Bavaro et al. (2018) opined that a characteristic of allergen proteins is their ability to resist the proteolytic processes within the gastrointestinal track, undergoing partial acidic and enzymatic hydrolysis on arrival at the intestinal mucosa and inducing sensitization when absorbed. Hashemi et al. (2023) further revealed that there was observed resistance of some protein fractions towards pepsin activity as well as responses to commercial antibodies especially the fractions associated with α-conglutin (20 kDa) and γ-conglutin (17 kDa) upon gastric digestion of lupin flour. Protein fractions including γ-conglutin has been shown to be resistant to pancreatin and trypsin enzymatic hydrolysis of lupin globulins (Hashemi et al. 2023). Czubiński et al. (2016) demonstrated that its insensitivity to enzymatic action might be due to the formation of complexes with flavonoids as well as the limited number of cleavage sites for trypsin. Processing forms such as thermal processing that results in denaturation, aggregation and chemical modifications, may affect hydrolysis during digestion. Czubinski et al. (2017) revealed that β-conglutin might undergo rearrangement during digestion thereby forming new allergens especially in individuals who have not demonstrated allergic symptoms before lupin consumption.

7 | Application of Lupin Protein in Novel Foods

Typically, proteins can have a wide range of applications in food formulation such as gelling agents, emulsifiers, nutrient supplements, encapsulates, additives, among others. The utilization of lupin protein in food formulation has emerged as a significant area of innovation and its successful application requires careful attention to down-stream processing.

7.1 | Lupin Protein-Based Emulsifier

The amphiphilic property of protein reduces the interfacial tension to stabilize the interface of water in oil or oil in water emulsion and plant protein-based emulsifiers can significantly affect the texture, mouthfeel, and viscosity of food products. However, native plant proteins impart emulsion instability due to poor surface hydrophilicity and therefore various process modifications of plant proteins have been performed to use as natural emulsifiers (Nikbakht Nasrabadi et al. 2020; Akharume et al. 2021; Ma et al. 2022). Ma et al. (2024) investigated the interfacial and foaming properties of LPIs at different pH values and found that LPI under acidic pH adsorbed faster at the air-water interface due to smaller particle size and higher surface hydrophobicity, resulting in higher foam overrun and stability. The study also revealed that LPI at acidic pH formed stiffer and more solid-like interfaces, leading to better foam stability compared to LPI at neutral pH.

It has been shown that processing can significantly affect the emulsifying property of lupin protein, with Bader, Bez, and Eisner (2011) and Bader, Oviedo, et al. (2011) revealing that HPH assisted in improving the emulsifying property of lupin protein. There was a significant reduction in the oil droplet size of the emulsion, which enhanced the emulsion stability, thereby enabling less creaming index. Lo et al. (2024) observed that the creaming index of lupin protein was shown to decrease by 6.9% due to HPH treatment. Besides lowering the creaming index, the pressure from HPH processing also causes a decrease in hydrophobic interaction of lupin protein, thereby saturating the surface of droplets to form a stable emulsion. Lo et al. (2024) and Keuleyan et al. (2023) further revealed that the flocculation index of HPH-treated lupin protein decreased almost 2.5-fold compared to the untreated lupin protein due to the increased electrostatic repulsion. Chukwuejim and Aluko (2024) who compared the emulsifying properties of blue lupin (*L. angustifolius*), white lupin (*L. albus*), and soybean protein isolates, reported that pH exerted an influence on the solubility of LPIs, with the lowest solubility recorded at pH 4–5. Emulsions stabilized by LPIs exhibited smaller oil droplet sizes at pH 7 and 9, indicating better emulsification properties. The study also highlighted that oil droplet coalescence was not the most prominent mechanism of emulsion instability for lupin isolates at acidic pH; instead, bridging flocculation was more significant, with the highest flocculation index at pH 5. These findings suggest that LPIs have strong potential as plant-based emulsifiers, particularly at neutral and alkaline pH levels. It indicates that LPI can be effectively used as a plant-based clean-label additive in foam-based food products, especially in acidic environments.

7.2 | Lupin Protein for Plant-Based Meat and Dairy Alternatives

Extrusion is currently the most widely applied plant protein texturization process in the production of plant-based meat alternatives. HME of a blend of LPI and protein concentrate (Table 4) showed high fiber meat-like microstructure with increasing temperature and screw speed along with decreasing moisture content (Palanisamy, Franke, et al. 2019; Ramos-Diaz et al. 2023). Another study on HME of the mixture of lupin protein and spirulina flour demonstrated the effect on texture, cooking yield, antioxidant properties, and nutritional profile of the meat analogue (Palanisamy, Töpfl, et al. 2019). Currently marketed meat alternative products containing lupin protein include plant-based sausage from Austrian vegan food company Velivery Ltd., processed by leveraging high protein content, natural binding properties, and firm-to-bite texture. Other companies like INVEJA have developed sustainable ingredient solutions, including lupin protein concentrates for various food applications.

Due to the low glycaemic index and high protein content compared to proteins from cereal and nuts, lupin protein-based products can be healthy alternatives. The ability of lupin protein to form stable emulsions and provide desirable mouthfeel characteristics could make it an attractive ingredient for dairy alternative applications. However, a comparison of different legume-based beverages including pea, chickpea and lupin as an alternative to dairy-based beverages demonstrated that despite the high protein content of lupin protein-based beverage, the chickpea protein-based beverage was shown to have a better taste and color (Lopes et al. 2020). A study on milk alternatives prepared from homogenized blue and white lupin protein at high pressure showed increased protein solubility (Vogelsang-O'Dwyer et al. 2022). Another study by Duarte, Mota, et al. (2022) demonstrated that controlling processing conditions plays a critical role in lupin protein, thereby improving its health benefits such as lowering anti-nutritional

TABLE 4 | Application of lupin protein in different plant-based foods.

Plant-based category	Product	Lupin component	Processing method	Key functional properties	Consumer acceptance	References
Meat alternatives	Texturized meat analogues	70% LPI:LPC blend + 30% native flour		Fibrous texture, water retention	ND	Ramos-Diaz et al. (2023)
	Meat analogues	Lupin protein mixture (lupin protein concentrate and isolate, 50:50)	HME	Temperature, screw speed and water feed affected fiber layers and IVPD	ND	Palanisamy, Franke, et al. (2019)
	Meat analogues	Lupin protein mixture (lupin protein isolate and lupin protein concentrate) and spirulina (15%, 30%, and 50%)	HME	Addition of spirulina increased polyphenolic content, antioxidant activity. Extruder characteristics had varying effect on IVPD	ND	Palanisamy, Töpfl, et al. (2019)
	Hamburgers	Debittered lupin + quinoa + corn	Baking	Favorable protein content with contribution of lysine and threonine	50% lupin substitute showed highest acceptability and digestibility	Chilón-Llico et al. (2022)
	Beef burger	5%, 10%, and 15% lupin seed flour	Steaming	Decrease of 16.11% fat, 6.37% protein and 43.22% cooking loss with increased moisture retention	No significant difference in lupin substituted steamed burger with control	Alrahaife and Abu-Alruz (2023)
	Meat analogues	Lupin protein base (lupin protein isolate)	Cooking	Protein content of 62.47%–82.46% and cooking yields of 79.47%–93.17%	Lupin protein-based meat analogue roasted at 140°C was the most preferred	Ayalew et al. (2024)
	High moisture meat analogues	Lupin flour + lupin protein isolate + soy protein isolate blends	Extrusion cooking	Increasing lupin flour reduced hardness, chewiness and gumminess. Feed moisture content increased antioxidant capacity and in vitro protein digestibility	ND	Elhordoy et al. (2025)
Dairy alternatives	Lupin milk	Lupin flour/protein		1.8%–2.4% protein, emulsification, creamy mouthfeel	Good sensory acceptance	Lopes et al. (2020)
	Lupin-oat yoghurt	Lupin-oat blend	Probiotic fermentation	High protein + fiber, creaminess	Rivals dairy creaminess	Dhakal, Kumar, et al. (2024), Dhakal, Younas, et al. (2024)
	Lupin-based yoghurt alternatives	Lupin protein base (lupin protein isolate)	Probiotic fermentation (*Lactobacillus plantarum*, *L brevis* and *Pediococcus pentosaceus*) on pasteurized (80°C for 60 s) and ultra-high temperature (140°C for 10 s) lupin-based milk	Lower tendency for syneresis. Heat treatment positively affected rheological and textural properties	ND	Hickisch et al. (2016)
	Lupin beverage	Lupin seeds + kefir grains	Prebiotic fermentation	Excellent antioxidant activities, increased free amino acids, and polysaccharide hydrolysis	ND	Łopusiewicz et al. (2020)

(Continues)

TABLE 4 | (Continued)

Plant-based category	Product	Lupin component	Processing method	Key functional properties	Consumer acceptance	References
	Lupin milk	Lupin sprouts and lupin seeds	Sprouting + pasteurization; cooking + pasteurization	Non-Newtonian fluids	Good appearance and color but low consistency and flavor	Lopes et al. (2020)
	Lupin dairy analogues	Lupin seeds	Probiotic fermentation; unfermented	Fermentation had varying effects on viscosity	Reduction in beany odor and unpleasant flavor; increase in sourness and vinegar odor due to fermentation	Laaksonen et al. (2021)
	Lupin milk	Lupin protein isolate	High pressure homogenization	Reduced particle size; greater stability; low in FODMAPs; low predicted glycemic index; and high in protein	ND	Vogelsang-O'Dwyer et al. (2022)
	Lupin cheese	Lupin milk proteins	Coagulation methods	Varying yield depending on number of filtrations; protein concentration of 20.6% and 27.3% for lupin cheese samples	Lupin cheese produced from 7.80% vinegar was most acceptable	Al-Saedi et al. (2021)
	Lupin beverage and yoghurt	Lupin seeds (dry, soaked and cooked)	Pasteurization; probiotic fermentation	Reduction of beany volatile compounds from beverages; 48% loss of flatulence sugars from beverage; good viscoelastic structure and flow properties; gel structure like soy yoghurt	Decrease in beany flavor (by 81% of panelist) in fermented beverage	Duarte, Nunes, et al. (2022)
	Lupin-oat yoghurt	Lupin flour + oat	Probiotic fermentation	Promotion of peptides through combination of probiotic cultures; similar functional properties of water holding capacity, consistency and firmness with dairy yoghurt	High sensory ratings and overall acceptability for lupin-oat yoghurt fermented with strains of *Lactobacillus plantarum* and *Bifidobacterium* species.	Dhakal, Kumar, et al. (2024), Dhakal, Younas, et al. (2024)
	Lupin oat-based milk and yoghurt analogues	Lupin flour + oat + lupin protein isolate	Probiotic fermentation	Addition of protein isolates improved water-holding capacity, firmness, cohesiveness and gel strength; reduction in FODMAPs content	ND	Dhakal et al. (2025)
	Lupin-based quark	Lupin paste	Probiotic fermentation using mixed cultures	Higher concentration of buttery aroma, umami-tasting glutamate and aspartate levels; reduced beany off-flavor	ND	Canoy et al. (2025)
	Lupin-based yoghurt	Lupin seeds	Probiotic fermentation	Lupin based yoghurt exhibited the highest antioxidant activities and total phenolic content compared to dairy and other yoghurt samples; higher firmness, cohesiveness and viscosity index values compared to other yoghurt samples	Lower scores for lupin-based yoghurt with increase in storage days	Cebi and Yangilar (2024)
	Lupin-based beverage	Lupin flour	High pressure homogenization with multiple passes	Increased pressure and multiple passes led to an increase in shelf life and dispersion stability as well as a decrease in microbial counts and particle size	ND	Xia et al. (2019)

(Continues)

TABLE 4 | (Continued)

Plant-based category	Product	Lupin component	Processing method	Key functional properties	Consumer acceptance	References
Egg alternatives	Egg substitute (cake)	Lupin milk	Baking	Higher L^* and b^* values of lupin cake; lower hardness	Decrease in overall acceptability	Aslan and Bilgicli (2022)
	Egg replacer (pound cake)	Lupin flour	Baking	Low specific volume; apparent viscosity of cake batter which is similar to that of whole egg	ND	Halm et al. (2024)

Abbreviations: FODMAPs, fermentable oligosaccharides, disaccharides, monosaccharides and polyols; HME, high moisture extrusion; IVPD, in vitro protein digestibility; ND, not determined.

level, enhancing protein digestion and bio-accessibility of micronutrients.

The combination of lupin and oat proteins in the development of yoghurt demonstrated a dairy-like creaminess and superior nutritional benefits when fermented with specific probiotic combinations such as *Lactobacillus plantarum* and *Bifidobacterium* (Dhakal et al. 2025). Such dairy-free cheese caters to the need of vegans and lactose intolerant populations. Elsamani et al. (2014) who investigated the effect of nutrition, microbial and sensory qualities of white cheese alternatives using concentrations of 25%, 50%, and 75% lupin protein, revealed that incorporation of a lupin-based milk alternative for cheese making could enhance the nutritional quality in terms of protein content. The study further showed improved taste, texture, flavor, and overall acceptability at a concentration of 25%. Furthermore, Asres et al. (2022) who compared the physicochemical and sensory properties of ice cream prepared by combining lupin protein with milk protein, demonstrated that ice cream using lupin protein exhibited better resistance against melting as well as enhanced overrun (84.05%) compared to the full dairy-based ice cream (83%). However, the crude fat content responsible for rich flavor, texture, and mouthfeel was found to be slightly lower in the vegan ice cream containing lupin (6.6%) compared to that of dairy ice cream (6.8%).

8 | Lupin Protein Life Cycle Assessment

The typical commodity production of current plant protein extracts or isolates incurs processes which involve energy and solvent-intensive steps. Currently, there is a scarcity of literature on the effect of extraction methods on energy or solvent consumption, thus hindering sustainability evaluations which limits any conclusion about upscaling feasibility in a sustainable way. A life cycle assessment (LCA) comparing conventional alkaline extraction with green, emerging technologies such as dry fractionation, SC-CO_2 and US is therefore critical. In establishing lupin as a serious alternative to other protein sources, Lucas et al. (2015) suggested that sustainability impacts as a key value-chain characteristic should be considered while combining LCA methods and participatory impact assessment techniques in a complimentary manner to assess the lupin supply chain. Rebolledo-Leiva et al. (2022) who applied the LCA methodology to determine the environmental impacts and economic implications of introducing lupin cultivation into winter wheat-based rotation systems in Spain, observed that the environmental performance of organic rotations with lupin is generally less impactful when compared to conventional systems without lupin. Lie-Piang et al. (2021) who performed an attributional LCA to compare the environmental impact of four different refining processes for protein-rich fractions from lupin and yellow pea, showed that reducing the degree of refining of lupin and yellow pea substantially lowers global warming potential, human carcinogenic toxicity, fossil resource scarcity and water consumption. However, drying remains the largest contributor to all impact categories. Vogelsang-O'Dwyer et al. (2020) examined the environmental impact of lupin and white LPIs conducted as an attributional cradle-to-gate assessment LCA. Their findings revealed that lupin isolates demonstrate considerably better performance in most categories when compared with traditional cow's whole milk powder.

The social life cycle assessment (sLCA) was used by Varela-Ortega et al. (2022) to compare the socio-economic impacts of legume-based food prototypes and conventional animal-based products across their life cycle. Socio-economic challenges such as lower farm-level net margin and profitability as well as worse protein affordability for consumers were observed for legume-based prototypes including lupin-based meat alternative, when compared to animal equivalents. Fernandez-Ríos et al. (2024) developed a new complex nutrient profile model, the quality Nutrient Rich Food 1.10.2′ (qNRF1.10.2) which combines various essential nutrients and DIAAS protein quality scoring system to efficiently evaluate the environmental implications of protein-rich foods through LCA. This method highlights lupin seeds as a vegetable food that reports low environmental impact as a function of their nutrient density and as among those having the best environmental performances when compared against other alternative and conventional protein sources. Berghout, Pelgrom, et al. (2015) who evaluated the sustainability of fractionation processes by considering the combination of dry and aqueous fractionation and skipping the final drying step, revealed that dry fractionation of lupin seeds is the most efficient method from an environmental perspective as it adds no water and requires no water to be evaporated.

9 | Challenges and Future Prospects

Published data on comparative analyses of the techno-functional properties between dry and wet isolates of lupin protein are scarce. A shift towards functionality-driven fractionation of lupin biomass could enable total raw material utilization, thereby supporting circular-economy principles. The lupin protein's inferior functional properties compared to soy protein constitute a challenge to lupin protein adoption. Thus, understanding the effect of novel food processing on the modification of the physicochemical and sensory properties of lupin protein would certainly assist to better design lupin protein-based food products. Non-thermal technologies such as US and HPH have shown impact on the microstructure modification and change in the techno-functional properties of lupin protein. However, this warrants further research into assessing the molecular basis of change in the physicochemical, microstructural and nutritional properties of lupin protein and how it affects the product properties. Furthermore, protein texturization leveraging HME remains understudied for lupin protein compared to mainstream soy and pea proteins. While water feed and screw speed significantly influence extrudate texture and digestibility, mechanistic insights into anisotropic structure formation are limited. To the best of our knowledge, there is hardly any study about understanding the novel texturization processes like shear cells or electrospinning applied so far to lupin protein.

A major challenge of plant-based dairy-free cheese is to mimic the melting behavior and stretchability of the dairy cheese. Research is therefore needed to assess whether foaming properties of lupin protein can be exploited to create specific microstructure which may help to improve the quality of plant-based cheese. Moreover, the beany off-flavor of legume protein limits the acceptability of pulse-based beverages and therefore further research is required in improving the sensory acceptability of lupin-based milk alternative especially with its low fatty acid profile when compared to other pulses like soy. On the other hand, protein digestibility is known to determine the quality of dietary protein, and in vitro studies reveal lupin protein digestibility ranges from 72% to 84% (Albe-Slabi et al. 2022; Chukwuejim and Aluko 2025). However, significant knowledge gaps still exist regarding protein digestibility across different extraction methods; how it is affected by other downstream processing such as extrusion, as well as bioavailability of lupin protein when compared to soy and animal proteins. Moreover, systematic studies on reducing anti-nutrients such as phytates and polyphenols through novel extraction methods are also needed to gain further scientific insights on how to improve the overall nutritional quality of lupin protein. Addressing these research priorities will therefore harness green technologies for developing sustainable lupin protein ingredients which should contribute to building resilient and future-fit global protein supply chains.

10 | Conclusions

Diversifying the current plant protein portfolio from environmental and biodiversity perspectives and an over reliance on soy is critical, and lupin could therefore play an important role as a sustainable protein source for the future food systems. With high protein content (30%–42%), essential amino acids, dietary fiber, and having low calorific starches, lupin offers strong nutritional credentials somewhat comparable to soybean. However, the presence of anti-nutrients, allergens, and the inferior organoleptic qualities of lupin proteins pose a challenge to the consumers' acceptance. The functional qualities of extracted lupin protein are significantly affected by the protein extraction process. It was observed that systematically altering pre-treatment of wet extraction conditions could be crucial for maximizing yield. Besides, novel extraction techniques including dry fractionation, SC-CO_2 extraction, and combined US-MW approaches demonstrate promise for improving protein yield and sustainability compared to conventional alkaline extraction. Earlier works using non-thermal processing technologies such as HPH and ultrasonication demonstrated some efficacy in enhancing the techno-functional properties of lupin protein via microstructural modifications. Nevertheless, in-depth research is still required to understand ways of controlling the microstructural change via non-thermal process which could enable lupin protein to overcome its techno-functional limitations.

With improved techno-functionalities, applications of lupin protein in mainstream plant-based meat and dairy alternatives as well as for emulsified products could have commercial potential, particularly in partially replacing soy protein in formulation. However, the path towards widespread adoption of lupin protein in the food industry necessitates overcoming identified technical and market-related hurdles. Further systematic research towards sustainable extraction of lupin protein devoid of anti-nutrients, developing functional fraction approaches and leveraging AI for process optimisation are crucial for maximizing functional efficacy. Detailed LCAs for both protein extraction and other down-stream processing for lupin protein are scarce and improving the sensory properties via fermentation and applying flavor masking strategies would be critical. Future research will certainly facilitate developing functionally modified lupin protein ingredients to enable more mainstream food applications.

Author Contributions

Vahid Baeghbali: writing – review and editing, visualization, validation, methodology, investigation, formal analysis, data curation. **Claire D. Munialo:** writing – review and editing, visualization, validation, data curation. **Tonna Ashim Anyasi:** writing – original draft, writing – review and editing, visualization, validation, data curation. **Parag Acharya:** conceptualization, writing – original draft, writing – review and editing, visualization, validation, methodology, formal analysis, funding acquisition, resources, supervision.

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Ethics Statement

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The authors have nothing to report.

References

Abraham, E. M., I. Ganopoulos, P. Madesis, et al. 2019. "The Use of Lupin as a Source of Protein in Animal Feeding: Genomic Tools and Breeding Approaches." *International Journal of Molecular Sciences* 20, no. 4: 851. https://doi.org/10.3390/ijms20040851.

Abreu, B., J. Lima, and A. Rocha. 2023. "Consumer Perception and Acceptability of Lupin-Derived Products: A Systematic Review." *Food* 12, no. 6: 1241. https://doi.org/10.3390/foods12061241.

Aghababaei, F., D. J. McClements, and M. Hadidi. 2025. "Strategies to Overcome Nutritional and Technological Limitations of Pulse Proteins." *Future Foods* 11: 100624. https://doi.org/10.1016/j.fufo.2025.100624.

Aguilar-Acosta, L. A., S. O. Serna-Saldivar, J. Rodríguez-Rodríguez, A. Escalante-Aburto, and C. Chuck-Hernández. 2020. "Effect of Ultrasound Application on Protein Yield and Fate of Alkaloids During Lupin Alkaline Extraction Process." *Biomolecules* 10, no. 2: 292. https://doi.org/10.3390/biom10020292.

Aguilera, J. M. 2019. "The Food Matrix: Implications in Processing, Nutrition and Health." *Critical Reviews in Food Science and Nutrition* 59: 3612–3629.

Aguilera, J. M., M. F. Gerngross, and E. W. Lusas. 1983. "Aqueous Processing of Lupin Seed." *International Journal of Food Science and Technology* 18: 327–333. https://doi.org/10.1111/j.1365-2621.1983.tb00275.x.

Ahmad, M., S. Qureshi, M. H. Akbar, et al. 2022. "Plant-Based Meat Alternatives: Compositional Analysis, Current Development and Challenges." *Applied Food Research* 2: 100154.

Akharume, F. U., R. E. Aluko, and A. A. Adedeji. 2021. "Modification of Plant Proteins for Improved Functionality: A Review." *Comprehensive Reviews in Food Science and Food Safety* 20, no. 1: 198–224. https://doi.org/10.1111/1541-4337.12688.

Albe-Slabi, S., O. Mesieres, C. Mathe, M. Ndiaye, O. Galet, and R. Kapel. 2022. "Combined Effect of Extraction and Purification Conditions on Yield, Composition and Functional and Structural Properties of Lupin Proteins." *Food* 11: 1646. https://doi.org/10.3390/foods11111646.

Allergome. 2023. "Allergome Database Entry: Lup a 4." https://www.allergome.org/.

Alrahaife, A. J., and K. Abu-Alruz. 2023. "Effects of Incorporation of Lupin Flour on the Quality Attributes of Beef Burger." *Online Journal of Animal and Feed Research* 13, no. 5: 328–339. https://doi.org/10.51227/ojafr.2023.48.

Al-Saedi, N., M. Agarwal, S. Islam, and Y.-L. Ren. 2021. "Study on the Correlation Between the Protein Profile of Lupin Milk and Its Cheese Production Compared With Cow's Milk." *Molecules* 26: 2395. https://doi.org/10.3390/molecules26082395.

Alu'datt, M. H., T. Rababah, M. N. Alhamad, et al. 2017. "Preparation of Mayonnaise From Extracted Plant Protein Isolates of Chickpea, Broad Bean and Lupin Flour: Chemical, Physiochemical, Nutritional and Therapeutic Properties." *Journal of Food Science and Technology* 54: 1395–1405. https://doi.org/10.1007/s13197-017-2551-6.

Amaral, D. F., J. B. de Souza Ferreira Filho, A. L. S. Chagas, and M. Adami. 2021. "Expansion of Soybean Farming Into Deforested Areas in the Amazon Biome: The Role and Impact of the Soy Moratorium." *Sustainability Science* 16: 1295–1312.

Anyiam, P. N., S. Phonghai, L. Grossman, et al. 2025. "Potential Plant Proteins for Functional Food Ingredients: Composition, Utilization and Its Challenges." *NFS Journal* 38: 100216.

Arnoldi, A., G. Boschin, C. Zanoni, and C. Lammi. 2015. "The Health Benefits of Sweet Lupin Seed Flours and Isolated Proteins." *Journal of Functional Foods* 18: 550–563.

Aslan, M., and N. Bilgicli. 2022. "The Comparison of Lupin Milk With Soy Milk as an Alternative Egg Substitute for Cake Production." *Journal of Food Processing and Preservation* 46: e16572. https://doi.org/10.1111/jfpp.16572.

Asres, A. M., H. W. Woldemariam, and F. G. Gemechu. 2022. "Physicochemical and Sensory Properties of Ice Cream Prepared Using Sweet Lupin and Soymilk as Alternatives to Cow Milk." *International Journal of Food Properties* 25, no. 1: 278–287. https://doi.org/10.1080/10942912.2022.2032733.

Australian Government. 2024. "Australia New Zealand Food Standards Code – Standard 1.2.3: Information Requirements – Warning Statements, Advisory Statements and Declarations." Federal Register of Legislation. https://www.legislation.gov.au/F2015L00397/latest.

Ayalew, D. B., B. D. Abera, and Y. L. Adiss. 2024. "Effect of Roasting Temperature and Soaking Time on the Nutritional, Antinutrional and Sensory Properties of Protein-Based Meat Analog From Lupine." *Heliyon* 10: e33122. https://doi.org/10.1016/j.heliyon.2024.e33122.

Bader, S., J. Bez, and P. Eisner. 2011. "Can Protein Functionalities Be Enhanced by High-Pressure Homogenization? – A Study on Functional Properties of Lupin Proteins." *Procedia Food Science* 1: 1359–1366. https://doi.org/10.1016/j.profoo.2011.09.201.

Bader, S., M. Czerny, P. Eisner, and A. Buettner. 2009. "Characterisation of Odour-Active Compounds in Lupin Flour." *Journal of the Science of Food and Agriculture* 89, no. 14: 2421–2427. https://doi.org/10.1002/jsfa.3739.

Bader, S., J. P. Oviedo, C. Pickardt, and P. Eisner. 2011. "Influence of Different Organic Solvents on the Functional and Sensory Properties of Lupin (*Lupinus angustifolius* L.) Proteins." *LWT - Food Science and Technology* 44: 1396–1404.

Bähr, M., A. Fechner, K. Hasenkopf, S. Mittermaier, and G. Jahreis. 2014. “Chemical Composition of Dehulled Seeds of Selected Lupin Cultivars in Comparison to Pea and Soya Bean.” *LWT* 59: 587–590.

Ballabio, C., C. Magni, P. Restani, et al. 2010. “IgE-Mediated Cross-Reactivity Among Leguminous Seed Proteins in Peanut-Allergic Children.” *Plant Foods for Human Nutrition* 65: 396–402. https://doi.org/10.1007/s11130-010-0199-8.

Barallat-Pérez, C., M. Pedrotti, T. Oliveira, S. Martins, V. Fogliano, and C. de Jong. 2024. “Drivers of the in-Mouth Interaction Between Lupin Protein Isolate and Selected Aroma Compounds: A Proton Transfer Reaction–Mass Spectrometry and Dynamic Time Intensity Analysis.” *Journal of Agricultural and Food Chemistry* 72, no. 15: 8731–8741. https://doi.org/10.1021/acs.jafc.3c08819.

Bartkiene, E., V. Sakiene, V. Bartkevics, et al. 2018. “*Lupinus angustifolius* L. Lactofermentation and Protein Isolation: Effects on Phenolic Compounds and Genistein, Antioxidant Properties, Trypsin Inhibitor Activity, and Protein Digestibility.” *European Food Research and Technology* 244: 1521–1531. https://doi.org/10.1007/s00217-018-3066-8.

Bavaro, S. L., L. Di Stasio, G. Mamone, et al. 2018. “Effect of Thermal/Pressure Processing and Simulated Human Digestion on the Immunoreactivity of Extractable Peanut Allergens.” *Food Research International* 109: 126–137. https://doi.org/10.1016/j.foodres.2018.04.021.

Berghout, J. A. M., R. M. Boom, and A. J. van der Goot. 2015. “Understanding the Differences in Gelling Properties Between Lupin Protein Isolate and Soy Protein Isolate.” *Food Hydrocolloids* 43: 465–472.

Berghout, J. A. M., P. J. M. Pelgrom, M. A. I. Schutyser, R. M. Boom, and A. J. van der Goot. 2015. “Sustainability Assessment of Oilseed Fractionation Processes: A Case Study on Lupin Seeds.” *Journal of Food Engineering* 150: 117–124. https://doi.org/10.1016/j.jfoodeng.2014.11.005.

Beyer, B., D. Obrist, P. Czarda, et al. 2024. “Influence of Roasting Temperature on the Detectability of Potentially Allergenic Lupin by SDS-PAGE, ELISAs, LC-MS/MS, and Real-Time PCR.” *Food* 13: 673. https://doi.org/10.3390/foods13050673.

Boukid, F., and A. Pasqualone. 2021. “Lupine (*Lupinus* spp.) Proteins: Characteristics, Safety and Food Applications.” *European Food Research and Technology* 248: 1–12. https://doi.org/10.1007/s00217-021-03909-5.

Canoy, T. S., J. Zwinkels, A. Dank, J. van Wiggen, J. C. M. Wolkers-Rooijackers, and E. J. Smid. 2025. “Starter Culture Design for the Development of a Novel Lupin-Based Quark With In Situ Vitamin B_{12} Fortification.” *LWT* 225: 117874. https://doi.org/10.1016/j.lwt.2025.117874.

Capraro, J., C. Magni, M. Fontanesi, A. Budelli, and M. Duranti. 2008. “Application of Two-Dimensional Electrophoresis to Industrial Process Analysis of Proteins in Lupin-Based Pasta.” *LWT* 41: 1011–1017.

Cebi, K., and F. Yangilar. 2024. “Comparative Analysis of Nutritional, Physicochemical, Microbiological, and Sensorial Characteristics of Dairy Yogurts Containing Probiotic Bacteria and Sandal Wood Essential Oil Versus Plant-Based Yogurts Made From Lupine Milk.” *European Journal of Lipid Science and Technology* 127: e202400147. https://doi.org/10.1002/ejlt.202400147.

Chang, C., A. K. Stone, R. Green, and M. T. Nickerson. 2019. “Reduction of Off-Flavours and the Impact on the Functionalities of Lentil Protein Isolate by Acetone, Ethanol, and Isopropanol Treatments.” *Food Chemistry* 277: 84–95. https://doi.org/10.1016/j.foodchem.2018.10.022.

Chapleau, N., and M. de Lamballerie-Anton. 2003. “Improvement of Emulsifying Properties of Lupin Proteins by High Pressure Induced Aggregation.” *Food Hydrocolloids* 17: 273–280.

Chew, P. G., A. J. Casey, and S. K. Johnson. 2003. “Protein Quality and Physico-Functionality of Australian Sweet Lupin (*Lupinus angustifolius* cv. Gungurru) Protein Concentrates Prepared by Isoelectric Precipitation or Ultrafiltration.” *Food Chemistry* 83: 575–583. https://doi.org/10.1016/S0308-8146(03)00156-0.

Chilón-Llico, R., L. Siguas-Cruzado, C. R. Apaza-Humerez, W. C. Morales-García, and R. J. Silva-Paz. 2022. “Protein Quality and Sensory Perception of Hamburgers Based on Quinoa, Lupin and Corn.” *Food* 11: 3405. https://doi.org/10.3390/foods11213405.

Chukwuejim, S., and R. E. Aluko. 2024. “Comparative Study of the Emulsifying Properties of Blue Lupin, White Lupin, and Soybean Protein Isolates.” *LWT* 206: 116544. https://doi.org/10.1016/j.lwt.2024.116544.

Chukwuejim, S., and R. E. Aluko. 2025. “Physicochemical and Functional Properties of Blue Lupin and White Lupin Protein Isolates.” *ACS Food Science & Technology* 5, no. 4: 1309–1321. https://doi.org/10.1021/acsfoodscitech.4c00877.

Chukwuejim, S., A. Utioh, T. D. Choi, and R. E. Aluko. 2024. “Lupin Seed Proteins: A Comprehensive Review of Composition, Extraction Technologies, Food Functionality, and Health Benefits.” *Food Reviews International* 40: 691–714. https://doi.org/10.1080/87559129.2023.2191701.

Crippa, M., E. Solazzo, D. Guizzardi, F. Monforti-Ferrario, F. N. Tubiello, and A. Leip. 2021. “Food Systems Are Responsible for a Third of Global Anthropogenic GHG Emissions.” *Nature Food* 2: 198–209.

Czubinski, J., M. Montowska, E. Springer, E. Pospiech, and E. Lampart-Szczapa. 2017. “Immunoreactivity Changes During Lupin Seed Storage Proteins Digestion.” *European Food Research and Technology* 243: 2095–2103. https://doi.org/10.1007/s00217-017-2910-6.

Czubiński, J., A. Siger, and E. Lampart-Szczapa. 2016. “Digestion Susceptibility of Seed Globulins Isolated From Different Lupin Species.” *European Food Research and Technology* 242: 391–403. https://doi.org/10.1007/s00217-015-2550-7.

D'Agostina, A., C. Antonioni, D. Resta, et al. 2006. “Optimization of a Pilot-Scale Process for Producing Lupin Protein Isolates With Valuable Technological Properties and Minimum Thermal Damage.” *Journal of Agricultural and Food Chemistry* 54, no. 1: 92–98. https://doi.org/10.1021/jf0518094.

David, L. S., C. L. Nalle, M. R. Abdollahi, and V. Ravindran. 2024. “Feeding Value of Lupins, Field Peas, Faba Beans and Chickpeas for Poultry: An Overview.” *Animals* 14, no. 4: 619. https://doi.org/10.3390/ani14040619.

Dhakal, D., G. Kumar, L. Devkota, D. Subedi, and S. Dhital. 2024. “The Choice of Probiotics Affects the Rheological, Structural, and Sensory Attributes of Lupin-Oat-Based Yoghurt.” *Food Hydrocolloids* 156: 110353. https://doi.org/10.1016/j.foodhyd.2024.110353.

Dhakal, D., J. Muir, D. Ni, and S. Dhital. 2025. “Lupin Protein Isolates Influence the Nutrition, Rheology, and Protein Profile of Lupin-Oat Yoghurt Analogues Through Probiotic Activity.” *Food Hydrocolloids* 169: 111618. https://doi.org/10.1016/j.foodhyd.2025.111618.

Dhakal, D., T. Younas, R. P. Bhusal, et al. 2024. “The Effect of Probiotic Strains on the Proteolytic Activity and Peptide Profiles of Lupin Oat-Based Yoghurt.” *Food Hydrocolloids* 149: 109570. https://doi.org/10.1016/j.foodhyd.2023.109570.

Domínguez, R., R. Bermúdez, M. Pateiro, R. Lucas-González, and J. M. Lorenzo. 2023. “Optimization and Characterization of Lupin Protein Isolate Obtained Using Alkaline Solubilization-Isoelectric Precipitation.” *Food* 12: 3875. https://doi.org/10.3390/foods12203875.

Dominguez-Valencia, R., R. Bermudez, M. Pateiro, L. Purrinos, J. Benedito, and J. M. Lorenzo. 2025. “Impact of Supercritical CO_2 Treatment on Lupin Flour and Lupin Protein Isolates.” *Food* 14: 675. https://doi.org/10.3390/foods14040675.

Dong, G., L. M. Hinds, A. B. Soro, Z. Hu, D. W. Sun, and B. K. Tiwari. 2024. “Non-Thermal Processing Technologies for Allergen Control in Alternative Protein Sources for Food Industry Applications.” *Food Engineering Reviews* 16, no. 4: 595–617. https://doi.org/10.1007/s12393-024-09378-2.

Dooper, M. M. B. W., L. Holden, C. K. Faste, K. M. Thompson, and E. Egaas. 2007. “Monoclonal Antibodies Against the Candidate Lupin Allergens α-Conglutin and β-Conglutin.” *International Archives of Allergy and Immunology* 143: 49–58. https://doi.org/10.1159/000098224.

Dreoni, I., Z. Matthews, and M. Schaafsma. 2022. “The Impacts of Soy Production on Multi-Dimensional Well-Being and Ecosystem Services: A Systematic Review.” *Journal of Cleaner Production* 335: 130182.

Duarte, C. M., J. Mota, R. Assuncao, et al. 2022. “New Alternatives to Milk From Pulses: Chickpea and Lupin Beverages With Improved Digestibility and Potential Bioactivities for Human Health.” *Frontiers in Nutrition* 9: 852907. https://doi.org/10.3389/fnut.2022.852907.

Duarte, C. M., M. C. Nunes, P. Gojard, et al. 2022. “Use of European Pulses to Produce Functional Beverages – From Chickpea and Lupin as Dairy Alternatives.” *Journal of Functional Foods* 98: 105287. https://doi.org/10.1016/j.jff.2022.105287.

Duluins, O., and P. V. Baret. 2024. “A Systematic Review of the Definitions, Narratives and Paths Forwards for a Protein Transition in High-Income Countries.” *Nature Food* 5: 28–36.

El-Adawy, T. A., E. H. Rahma, A. A. El-Bedawey, and A. F. Gafar. 2001. “Nutritional Potential and Functional Properties of Sweet and Bitter Lupin Seed Protein Isolates.” *Food Chemistry* 74: 455–462.

Elhordoy, M. R., A. Kadam, D. Vazquez, A. Medrano, and F. Koksel. 2025. “Exploring the Potential of Lupin (*Lupinus angustifolius*) Flour-Based Ingredients in Developing High Moisture Meat Analogues.” *Journal of Food Science* 90: e70407. https://doi.org/10.1111/1750-3841.70407.

Elsamani, M. O., S. S. Habbani, E. E. Babiker, and I. A. Mohamed Ahmed. 2014. “Biochemical, Microbial and Sensory Evaluation of White Soft Cheese Made From Cow and Lupin Milk.” *LWT - Food Science and Technology* 59, no. 1: 553–559. https://doi.org/10.1016/j.lwt.2014.04.027.

European Food Safety Authority. 2006. “Opinion of the Scientific Panel on Dietetic Products, Nutrition and Allergies Related to the Evaluation of Lupin for Labelling Purposes.” *EFSA Journal* 4, no. 1: 302. https://doi.org/10.2903/j.efsa.2006.302.

European Parliament and Council. 2006. “Directive 2006/142/EC Amending Annex IIIa of Directive 2000/13/EC, Listing the Ingredients That Must Under all Circumstances Appear on the Labelling of Foodstuffs.”

European Parliament and Council. 2011. “Regulation (EU) No 1169/2011 on the Provision of Food Information to Consumers.” Official Journal of the European Union, L304, 22 November. http://data.europa.eu/eli/reg/2011/1169/2025-04-01.

Faeste, C. K. 2010. “Lupin Allergen Aetection.” In *Molecular Biological and Immunological Techniques and Applications for Food Chemists*, edited by B. Popping, C. Diaz-Amigo, and K. Hoenicke, 423–444. John Wiley & Sons, Inc.

Fernandez-Ríos, A., L. Batlle-Bayer, S. Azarkamand, et al. 2024. “Development and Application of a Nutritional Quality Model for Life Cycle Assessment of Protein-Rich Foods.” *Sustainable Production and Consumption* 50: 35–44. https://doi.org/10.1016/j.spc.2024.07.026.

Fontanari, G. G., J. M. Martins, M. Kobelnik, et al. 2012. “Thermal Studies on Protein Isolates of White Lupin Seeds (*Lupinus albus*).” *Journal of Thermal Analysis and Calorimetry* 108: 141–148. https://doi.org/10.1007/s10973-011-1898-6.

FSANZ. 2017. “Proposal P1026: Lupin as an Allergen – Approval Report. Food Standards Australia New Zealand.” Accessed December 30, 2025. https://www.foodstandards.gov.au/sites/default/files/food-standards-code/proposals/Documents/P1026%20Lupin%20as%20an%20allergen%20AppR.docx.

Geng, Q., Y. Zhang, M. Song, et al. 2023. “Allergenicity of Peanut Allergens and Its Dependence on the Structure.” *Comprehensive Reviews in Food Science and Food Safety* 22, no. 2: 1058–1081.

Goggin, D. E., G. Mir, W. B. Smith, M. Stuckey, and P. M. C. Smith. 2008. “Proteomic Analysis of Lupin Seed Proteins to Identify Conglutin β as an Allergen, Lup an 1.” *Journal of Agricultural and Food Chemistry* 56: 6370–6377. https://doi.org/10.1021/jf800840u.

Gresta, F., M. Wink, U. Prins, et al. 2017. “Lupins in European Cropping Systems.” In *Legumes in Cropping Systems*, edited by D. Murphy-Bokem, F. L. Stoddard, and C. A. Watson, 88–108. CABI International. https://doi.org/10.1079/9781780644981.0088.

Guarneri, F., C. Guarneri, and S. Benvenga. 2005. “Identification of Potentially Cross-Reactive Peanut-Lupine Proteins by Computer-Assisted Search for Amino Acid Sequence Homology.” *International Archives of Allergy and Immunology* 138: 273–277. https://doi.org/10.1159/000088864.

Gunal-Koroglu, D., G. Karabulut, G. Ozkan, H. Yılmaz, B. Gultekin-Subası, and E. Capanoglu. 2025. “Allergenicity of Alternative Proteins: Reduction Mechanisms and Processing Strategies.” *Journal of Agricultural and Food Chemistry* 73: 7522–7546. https://doi.org/10.1021/acs.jafc.5c00948.

Halm, J., A. W. Sahin, L. Nyhan, E. Zannini, and E. K. Arendt. 2024. “Commercial Egg Replacers in Pound Cake Systems: A Comprehensive Analysis of Market Trends and Application.” *Food* 13: 292. https://doi.org/10.3390/foods13020292.

Hashemi, N., S. L. Bavaro, and M. Corredig. 2023. “Effect of Heat Treatment on Lupin Reactivity Against Rabbit Polyclonal Antibodies After In Vitro Gastrointestinal Digestion.” *Sustainable Food Proteins* 2: 21–32. https://doi.org/10.1002/sfp2.1024.

Herreman, L., P. Nommnsen, B. Pennings, and M. C. Laus. 2020. “Comprehensive Overview of the Quality of Plant- and Animal sourced Proteins Based on the Digestible Indispensable Amino Acid Score.” *Food Science & Nutrition* 8, no. 10: 5379–5391. https://doi.org/10.1002/fsn3.1809.

Hickisch, A., R. Beer, R. F. Vogel, and S. Toelstede. 2016. “Influence of Lupin-Based Milk Alternative Heat Treatment and Exopolysaccharide-Producing Lactic Acid Bacteria on the Physical Characteristics of Lupin-Based Yogurt Alternatives.” *Food Research International* 84: 180–188. https://doi.org/10.1016/j.foodres.2016.03.037.

Holden, L., G. B. G. Sletten, H. Lindvik, C. K. Fæste, and M. M. B. W. Dooper. 2008. “Characterization of IgE Binding to Lupin, Peanut and Almond With Sera From Lupin Allergic Patients.” *International Archives of Allergy and Immunology* 146: 267–276.

Huang, Z., L. Pang, S. Li, et al. 2024. “Effects of Physical Processing on Food Protein Allergenicity: A Focus on Differences Between Animal and Alternative Proteins.” *Food Chemistry* 460: 140559. https://doi.org/10.1016/j.foodchem.2024.140559.

Jadhav, H. B., M. Das, A. Das, et al. 2024. “Enhancing the Functionality of Plant-Based Proteins With the Application of Ultrasound–A Review.” *Measurement: Food* 13: 100139. https://doi.org/10.1016/j.meafoo.2024.100139.

Jappe, U., A. Karstedt, D. Warneke, et al. 2021. “Identification and Purification of Novel Low-Molecular-Weight Lupine Allergens as Components for Personalized Diagnostics.” *Nutrients* 13: 409. https://doi.org/10.3390/nu13020409.

Jappe, U., and S. Vieths. 2010. “Lupine, a Source of New as Well as Hidden Food Allergens.” *Molecular Nutrition & Food Research* 54: 113–126.

Jiménez-Saiz, R., S. Benedé, E. Molina, and I. Lopez-Exposito. 2015. “Effect of Processing Technologies on the Allergenicity of Food Products.” *Critical Reviews in Food Science and Nutrition* 55: 1902–1917. https://doi.org/10.1080/10408398.2012.736435.

Keuleyan, E., P. Gelebart, V. Beaumal, et al. 2023. “Pea and Lupin Protein Ingredients: New Insights Into Endogenous Lipids and the Key Effect of High-Pressure Homogenization on Their Aqueous

Suspensions." *Food Hydrocolloids* 141: 108671. https://doi.org/10.1016/j.foodhyd.2023.108671.

Khalid, I. I., and S. B. Elharadallou. 2013. "Functional Properties of Cowpea (*Vigna ungiculata L. Walp*), and Lupin (*Lupinus termis*) Flour and Protein Isolates." *Journal of Nutrition & Food Sciences* 3, no. 6: 234. https://doi.org/10.4172/2155-9600.1000234.

Kim, W., Y. Wang, and C. Selomulya. 2020. "Dairy and Plant Proteins as Natural Food Emulsifiers." *Trends in Food Science & Technology* 105: 261–272.

Kohajdová, Z., J. Karovičová, and Š. Schmidt. 2011. "Lupin Composition and Possible Use in Bakery – A Review." *Czech Journal of Food Sciences* 29, no. 3: 203–211. https://doi.org/10.17221/252/2009-CJFS.

Laaksonen, O., M. Kahala, A. Marsol-Vall, et al. 2021. "Impact of Lactic Acid Fermentation on Sensory and Chemical Quality of Dairy Analogues Prepared From Lupine (*Lupinus angustifolius* L.) Seeds." *Food Chemistry* 346: 128852. https://doi.org/10.1016/j.foodchem.2020.128852.

Lam, A. C. Y., A. Can Karaca, R. T. Tyler, and M. T. Nickerson. 2018. "Pea Protein Isolates: Structure, Extraction, and Functionality." *Food Reviews International* 34: 126–147.

Leduc, V., D. A. Moneret-Vautrin, and L. Guerin. 2002. "Allergénicité de la farine de lupin." *Allergie et Immunologie* 34: 213–217.

Lie-Piang, A., N. Braconi, R. M. Boom, and A. van der Padt. 2021. "Less Refined Ingredients Have Lower Environmental Impact–a Life Cycle Assessment of Protein-Rich Ingredients From Oil-and Starch-Bearing Crops." *Journal of Cleaner Production* 292: 126046. https://doi.org/10.1016/j.jclepro.2021.126046.

Lima-Cabello, E., J. D. Alche, and J. C. Jimenez-Lopez. 2019. "Narrow Leafed Lupin Main Allergen β-Conglutin (Lup an 1) Detection and Quantification Assessment in Natural and Processed Foods." *Food* 8, no. 10: 513. https://doi.org/10.3390/foods8100513.

Lima-Cabello, E., V. Alche, R. C. Foley, et al. 2016. "Narrow-Leafed Lupin (*Lupinus angustifolius* L.) β-Conglutin Proteins Modulate the Insulin Signaling Pathway as Potential Type 2 Diabetes Treatment and Inflammatory-Related Disease Amelioration." *Molecular Nutrition & Food Research* 61, no. 5: 1600819. https://doi.org/10.1002/mnfr.201600819.

Lo, B., S. Kasapis, and A. Farahnaky. 2021. "Lupin Protein: Isolation and Techno-Functional Properties, a Review." *Food Hydrocolloids* 112: 106318.

Lo, B., S. Kasapis, and A. Farahnaky. 2022. "Effect of Low Frequency Ultrasound on the Functional Characteristics of Isolated Lupin Protein." *Food Hydrocolloids* 124: 107345. https://doi.org/10.1016/j.foodhyd.2021.107345.

Lo, B., S. Kasapis, and A. Farahnaky. 2024. "Improving Functional Properties of Lupin Protein by Physical Modification: High Pressure Homogenisation." *International Journal of Food Science and Technology* 59: 1443–1455. https://doi.org/10.1111/ijfs.16892.

Lopes, M., C. Pierrepont, A. F. Duarte, B. Medronho, and I. Sousa. 2020. "Legume Beverages From Chickpea and Lupin, as New Milk Alternatives." *Food* 9: 1458. https://doi.org/10.3390/foods9101458.

Łopusiewicz, Ł., E. Drozłowska, P. Trocer, et al. 2020. "The Effect of Fermentation With Kefir Grains on the Physicochemical and Antioxidant Properties of Beverages From Blue Lupin (*Lupinus angustifolius* L.) Seeds." *Molecules* 25, no. 24: 5791. https://doi.org/10.3390/molecules25245791.

Lucas, M. M., F. L. Stoddard, P. Annicchiarico, et al. 2015. "The Future of Lupin as a Protein Crop in Europe." *Frontiers in Plant Science* 6: 705. https://doi.org/10.3389/fpls.2015.00705.

Ma, K. K., M. Greis, J. Lu, A. A. Nolden, D. J. McClements, and A. J. Kinchla. 2022. "Functional Performance of Plant Proteins." *Food* 11, no. 4: 594. https://doi.org/10.3390/foods11040594.

Ma, X., M. Habibi, and L. M. C. Sagis. 2024. "Interfacial and Foaming Properties of Soluble Lupin Protein Isolates: Effect of pH." *Food Hydrocolloids* 155: 110228. https://doi.org/10.1016/j.foodhyd.2024.110228.

Mane, S. P., S. K. Johnson, M. Duranti, V. K. Pareek, and R. P. Utikar. 2018. "Lupin Seed γ-Conglutin: Extraction and Purification Methods - A Review." *Trends in Food Science & Technology* 73: 1–11. https://doi.org/10.1016/j.tifs.2017.12.008.

Monteiro, M. R. P., A. B. P. Costa, S. F. Campos, et al. 2014. "Evaluation of the Chemical Composition, Protein Quality and Digestibility of Lupin (*Lupinus albus* and *Lupinus angustifolius*)." *O Mundo da Saude (Sao Paulo)* 38: 251–259.

Munialo, C. D., V. Baeghbali, and P. Acharya. 2025. "Plant-Based Alternatives to Meat Products." *Food* 14: 1396. https://doi.org/10.3390/foods14081396.

Munialo, C. D., D. Stewart, L. Campbell, and S. R. Euston. 2022. "Extraction, Characterisation and Functional Applications of Sustainable Alternative Protein Sources for Future Foods: A Review." *Future Foods* 6: 100152.

Munialo, C. D., and F. Vriesekoop. 2023. "Plant-Based Foods as Meat and Fat Substitutes." *Food Science & Nutrition* 11: 4898–4911.

Navarro-Vozmediano, P., E. Dalmau, J. Benedito, and J. V. Garcia-Perez. 2025. "High-Power Ultrasound Pretreatment for Enhanced Protein Extraction From Lupin Flour: Impact on Yield, Anti-Technological and Anti-Nutritional Factors, and Techno-Functional Properties." *Ultrasonics Sonochemistry* 114: 107251. https://doi.org/10.1016/j.ultsonch.2025.107251.

Nikbakht Nasrabadi, M., A. Sedaghat Doost, and R. Mezzenga. 2020. "Modification Approaches of Plant-Based Proteins to Improve Their Techno-Functionality and Use in Food Products." *Food Hydrocolloids* 118: 106789.

Palanisamy, M., K. Franke, R. G. Berger, V. Heinz, and S. Töpfl. 2019. "High Moisture Extrusion of Lupin Protein: Influence of Extrusion Parameters on Extruder Responses and Product Properties." *Journal of the Science of Food and Agriculture* 99: 2175–2185. https://doi.org/10.1002/jsfa.9410.

Palanisamy, M., S. Töpfl, R. G. Berger, and C. Hertel. 2019. "Physico-Chemical and Nutritional Properties of Meat Analogues Based on Spirulina/Lupin Protein Mixtures." *European Food Research and Technology* 245: 1889–1898. https://doi.org/10.1007/s00217-019-03298-w.

Pelgrom, P. J. M., J. A. M. Berghout, A. J. van der Goot, R. M. Boom, and M. A. I. Schutyser. 2014. "Preparation of Functional Lupine Protein Fractions by Dry Separation." *LWT - Food Science and Technology* 59: 680–688. https://doi.org/10.1016/j.lwt.2014.06.007.

Politiek, R. G. A., E. Pegiou, L. L. Balfoort, M. E. Bruins, M. A. I. Schutyser, and J. K. Keppler. 2023. "Functional and Flavour Properties of de-Oiled Flours and Dry-Enriched Protein Concentrates of Lupin and Soy." *Future Foods* 8: 100274. https://doi.org/10.1016/j.fufo.2023.100274.

Rababah, T., M. Al Udatt, S. Angor, et al. 2023. "Nutraceutical and Functional Properties of Lupin Protein Extracts Obtained via a Combined Ultrasonication and Microwave-Assisted Process." *PRO* 11: 2858. https://doi.org/10.3390/pr11102858.

Ramos-Diaz, J. M., S. Oksanen, K. Kantanen, et al. 2023. "Characterization of Texturized Meat Analogues Containing Native Lupin Flour and Lupin Protein Concentrate/Isolate." *Heliyon* 9: e20503. https://doi.org/10.1016/j.heliyon.2023.e20503.

Rebolledo-Leiva, R., F. Almeida-García, S. Pereira-Lorenzo, B. Ruíz-Nogueira, M. T. Moreiraa, and S. González-García. 2022. "Determining the Environmental and Economic Implications of Lupin Cultivation in Wheat-Based Organic Rotation Systems in Galicia, Spain." *Science of the Total Environment* 845: 157342. https://doi.org/10.1016/j.scitotenv.2022.157342.

Riquelme, N., P. Díaz-Calderón, A. Luarte, and C. Arancibia. 2025. "Effect of Ultrasound Time on Structural and Gelling Properties of Pea, Lupin, and Rice Proteins." *Gels* 11: 270. https://doi.org/10.3390/gels11040270.

Risha, M. A., E.-M. Rick, M. Plum, and U. Jappe. 2024. "Legume Allergens Pea, Chickpea, Lentil, Lupine and Beyond." *Current Allergy and Asthma Reports* 24: 527–548. https://doi.org/10.1007/s11882-024-01165-7.

Rodríguez-Ambriz, S. L., A. L. Martínez-Ayala, F. Millán, and G. Dávila-Ortíz. 2005. "Composition and Functional Properties of Lupinus Campestris Protein Isolates." *Plant Foods for Human Nutrition* 60: 99–107. https://doi.org/10.1007/s11130-005-6835-z.

Schindler, S., M. Wittig, K. Zelena, et al. 2011. "Lactic Fermentation to Improve the Aroma of Protein Extracts of Sweet Lupin (*Lupinus angustifolius*)." *Food Chemistry* 128, no. 2: 330–337. https://doi.org/10.1016/j.foodchem.2011.03.024.

Schlegel, K., A. Leidigkeit, P. Eisner, and U. Schweiggert-Weisz. 2019. "Technofunctional and Sensory Properties of Fermented Lupin Protein Isolates." *Food* 8, no. 12: 678. https://doi.org/10.3390/foods8120678.

Schlegel, K., K. Sontheimer, A. Hickisch, A. A. Wani, P. Eisner, and U. Schweiggert-Weisz. 2019. "Enzymatic Hydrolysis of Lupin Protein Isolates—Changes in the Molecular Weight Distribution, Technofunctional Characteristics, and Sensory Attributes." *Food Science & Nutrition* 7, no. 8: 2747–2759. https://doi.org/10.1002/fsn3.1139.

Shenghua, H., W. Yonghui, and D. Qianchun. 2021. "Physicochemical Properties of Lupin Proteins Extracted by Micellization or Alkali Dissolution Followed by Acid Precipitation." *Food Science* 43, no. 8: 36–43. https://doi.org/10.7506/spkx1002-6630-20210525-300.

Shrestha, S., L. van 't. Hag, V. S. Haritos, and S. Dhital. 2021. "Lupin Proteins: Structure, Isolation and Application." *Trends in Food Science and Technology* 116: 928–939.

Sim, S. Y. J., A. Srv, J. H. Chiang, and C. J. Henry. 2021. "Plant Proteins for Future Foods: A Roadmap." *Food* 10: 1967.

Smith, K., A. W. Watson, M. Lonnie, et al. 2024. "Meeting the Global Protein Supply Requirements of a Growing and Ageing Population." *European Journal of Nutrition* 63: 1425–1433. https://doi.org/10.1007/s00394-024-03358-2.

Sussmann, D., C. Pickardt, U. Schweiggert, and P. Eisner. 2013. "Influence of Different Processing Parameters on the Isolation of Lupin (*Lupinus angustifolius* L.) Protein Isolates: A Preliminary Study." *Journal of Food Process Engineering* 36, no. 1: 18–28. https://doi.org/10.1111/j.1745-4530.2011.00647.x.

Tadesse, D. Z. 2021. "Production and Characterization of Protein Isolate From White Lupin (*Lupin albus*) Seed." Master's Thesis, Faculty of Chemical and Food Engineering, Bashir Dar Institute of Technology, Ethiopia. http://ir.bdu.edu.et/handle/123456789/12426.

Tan, E.-S., N. Ying-Yuan, and C.-Y. Gan. 2014. "A Comparative Study of Physicochemical Characteristics and Functionalities of Pinto Bean Protein Isolate (PBPI) Against the Soybean Protein Isolate (SPI) After the Extraction Optimisation." *Food Chemistry* 152: 447–455. https://doi.org/10.1016/j.foodchem.2013.12.008.

Tang, J., L. Cases, S. Alves, D. W. Sun, and B. K. Tiwari. 2025. "Protein Extraction From Lupin (*Lupinus angustifolius* L.) Using Combined Ultrasound and Microwave Techniques: Impact on Protein Recovery, Structure, and Functional Properties." *Ultrasonics Sonochemistry* 115: 107232. https://doi.org/10.1016/j.ultsonch.2025.107232.

Varela-Ortega, C., I. Blanco-Gutiérrez, R. Manners, and A. Detzel. 2022. "Life Cycle Assessment of Animal-Based Foods and Plant-Based Protein-Rich Alternatives: A Socio-Economic Perspective." *Journal of the Science of Food and Agriculture* 102, no. 12: 5111–5120. https://doi.org/10.1002/jsfa.11655.

Vellinga, T. V., and M. de Vries. 2018. "Effectiveness of Climate Change Mitigation Options Considering the Amount of Meat Produced in Dairy Systems." *Agricultural Systems* 162: 136–144.

Verma, A. K., S. Kumar, M. Das, and P. D. Dwivedi. 2013. "A Comprehensive Review of Legume Allergy." *Clinical Reviews in Allergy & Immunology* 45: 30–46. https://doi.org/10.1007/s12016-012-8310-6.

Villa, C., M. B. M. V. Moura, J. Costa, and I. Mafra. 2020. "Immunoreactivity of Lupine and Soybean Allergens in Foods as Affected by Thermal Processing." *Food* 9, no. 3: 254. https://doi.org/10.3390/foods9030254.

Vogelsang-O'Dwyer, M., A. W. Sahin, E. Zannini, and E. K. Arendt. 2022. "Physicochemical and Nutritional Properties of High Protein Emulsion-Type Lupin-Based Model Milk Alternatives: Effect of Protein Source and Homogenization Pressure." *Journal of the Science of Food and Agriculture* 102: 5086–5097. https://doi.org/10.1002/jsfa.11230.

Vogelsang-O'Dwyer, M. J., I. L. Bez, I. L. Petersen, et al. 2020. "Techno-Functional, Nutritional and Environmental Performance of Protein Isolates From Blue Lupin and White Lupin." *Food* 9: 230. https://doi.org/10.3390/foods9020230.

von Greyerz, K., P. Tidåker, J. O. Karlsson, and E. Röös. 2023. "A Large Share of Climate Impacts of Beef and Dairy Can Be Attributed to Ecosystem Services Other Than Food Production." *Journal of Environmental Management* 325: 116400.

Wang, D., J. Wang, Y. Lang, et al. 2025. "Interactions Between Food Matrices and Odorants: A Review." *Food Chemistry* 466: 142086. https://doi.org/10.1016/j.foodchem.2024.142086.

Wang, Q., and Y. L. Xiong. 2019. "Processing, Nutrition, and Functionality of Hempseed Protein: A Review." *Comprehensive Reviews in Food Science and Food Safety* 18: 936–952. https://doi.org/10.1111/1541-4337.12450.

Wang, Y., F. Tuccillo, A.-M. Lampi, et al. 2022. "Flavor Challenges in Extruded Plant-Based Meat Alternatives: A Review." *Comprehensive Reviews in Food Science and Food Safety* 21: 2898–2929. https://doi.org/10.1111/1541-4337.12964.

Wanniarachchi, P. C., G. Shea, M. Mocerino, S. J. Bennett, R. R. Bhattarai, and R. Coorey. 2025. "What Makes Lupins Less Palatable to Consumers? Can the Sensory Quality of Lupin Be Improved and Commercialized?" *Comprehensive Reviews in Food Science and Food Safety* 24, no. 5: e70265. https://doi.org/10.1111/1541-4337.70265.

WHO/IUIS. n.d. "Allergen Nomenclature – Search Database." Accessed December 30, 2025. https://www.allergen.org/.

Wong, A., K. Pitts, V. Jayasena, and S. Johnson. 2013. "Isolation and Foaming Functionality of Acid-Soluble Protein From Lupin (*Lupinus angustifolius*) Kernels." *Journal of the Science of Food and Agriculture* 93: 3755–3762. https://doi.org/10.1002/jsfa.6249.

Xia, X., Y. Dai, H. Wu, et al. 2019. "Effects of Pressure and Multiple Passes on the Physicochemical and Microbial Characteristics of Lupin-Based Beverage Treated With High-Pressure Homogenization." *Journal of Food Processing and Preservation* 43: e13912. https://doi.org/10.1111/jfpp.13912.

Yang, J., and L. M. C. Sagis. 2021. "Interfacial Behavior of Plant Proteins—Novel Sources and Extraction Methods." *Current Opinion in Colloid & Interface Science* 56: 101499. https://doi.org/10.1016/j.cocis.2021.101499.

Zhou, F., S. He, H. Sun, Y. Wang, and Y. Zhang. 2021. "Advances in Epitope Mapping Technologies for Food Protein Allergens: A Review." *Trends in Food Science & Technology* 107: 226–239.