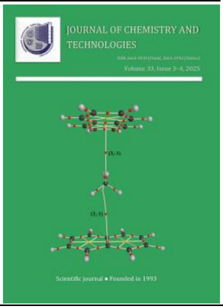
Journal of Chemistry and Technologies, 2025, *33*(3), 1092-1117

Journal of Chemistry and Technologies

pISSN 2663-2934 (Print), ISSN 2663-2942 (Online).

journal homepage: http://chemistry.dnu.dp.ua
editorial e-mail: chem.dnu@gmail.com



UDC 664.87

ANALYSIS OF MODERN METHODS OF LEGUME PROCESSING AND THEIR IMPACT ON THE NUTRITIONAL VALUE AND DIGESTIBILITY OF RAW MATERIALS

Yevheniia V. Chebanenko[1], Oksana Yu. Melnyk [1], Valentyn A. Cherniakov[1], Tatiana A. Naumenko[1], Andriy V. Sharan[2], Mikhailo F. Kravchenko[3], Liliya L. Ivashina[4], Viktor M. Fedoriv[5], Eduard V. Prokopenko[6]

[1]Sumy National Agrarian University, 160 Gerasima Kondratieva Srt., 40021, Sumy, Ukraine
[2]National University of Food Technologies, 68 Volodymyrska Str., 01601, Kyiv, Ukraine
[3]State University of Trade and Economics, 19 Kyoto Str., 02156, Kyiv, Ukraine
[4]Cherkasy State Technological University, 460 Shevchenko Boulevard, 18006, Cherkasy, Ukraine
[5]Khmelnytskyi National University, 11 Instytutska Str., 29016, Khmelnytskyi, Ukraine
[6]Uman National University, 1 Instytutska Str., 20300, Uman, Ukraine

Received 28 May 2025; accepted 15 November 2025; available online 25 December 2025

Abstract

This review article systematically analyzes and synthesizes current scientific literature on modern innovative methods of legume processing and their impact on nutritional value, functional properties, and sensory characteristics of final products. Key technologies, including fermentation, ultrasonic processing, high-pressure processing, extrusion, microwave and infrared heating, and electromagnetic field treatment, are critically reviewed and compared. Particular attention is focused on synthesizing reported data on the reduction of anti-nutrients, increasing the bioavailability of proteins and trace elements, and improving the texture and taste of legume-based products. This review analyzes the scientific basis and technological principles of each method and highlights literature-reported mechanisms through which they affect the structural and chemical composition of pulses. The synergistic effects of combined processing methods are discussed in the context of improved nutrient retention, reduced energy consumption, and enhanced processing efficiency. The synthesis of the literature indicates that these methods contribute to expanding the use of pulses in the food industry, particularly in the production of high-protein snacks, meat and dairy alternatives, gluten-free products, and functional foods with targeted health benefits. These technologies support sustainable and innovative food systems by increasing the value of pulses as affordable and environmentally friendly protein sources. In addition, special attention is dedicated to integrated processing approaches that combine several advanced methods to achieve high efficiency in improving the nutritional, physicochemical, and sensory properties of pulses. This review identifies the importance of process optimization, scaling-up potential, and the impact of processing conditions on product quality and consumer acceptance. The findings of this review can be used to develop novel food products, optimize production processes, increase supply chain sustainability, and guide further research in plant-based processing technologies. This review emphasizes the strategic role of pulses in supporting global food security and the transition to healthier and more sustainable diets.

Keywords: legumes; processing; bioavailability; fermentation; ultrasound; high pressure; extrusion; electromagnetic fields; infrared heating; microwave processing; food safety.

АНАЛІЗ СУЧАСНИХ МЕТОДІВ ОБРОБКИ БОБОВИХ ТА ЇХ ВПЛИВУ НА ПОЖИВНУ ЦІННІСТЬ ТА ЗАСВОЮВАНІСТЬ СИРОВИНИ

Євгенія В. Чебаненко[1], Оксана Ю. Мельник[1], Валентин А. Черняков[1], Тетяна А. Науменко[1], Андрій В. Шаран[2], Михайло Ф. Кравченко[3], Лілія Л. Івашина[4], Віктор М. Федорів[5], Едуард В. Прокопенко[6]

[1]Сумський національний аграрний університет, вул. Герасима Кондратьєва, 160, м. Суми, 40000, Україна
[2]Національний університет харчових технологій, вул. Володимирська, 68, 01601, Київ, Україна
[3]Державний університет торгівлі та економіки, вул. Кіото, 19, 02156, Київ, Україна
[4]Черкаський державний технологічний університет, бульвар Шевченка, 460, 18006, м. Черкаси, Україна
[5]Хмельницький національний університет, вул. Інститутська, 11, 29016, м. Хмельницький, Україна
[6]Уманський національний університет, вул. Інститутська, 1, 20300, м. Умань, Україна

Анотація

У даній оглядовій статті проведений комплексний аналіз сучасних інноваційних методів обробки бобових культур, спрямованих на підвищення їх поживної цінності, функціональних і сенсорних якостей. Під час

**Corresponding author: e-mail: evgeniachebanenko@gmail.com*
 doi: 10.15421/jchemtech.v33i4.331093

аналізу наукової літератури проаналізовані ключові технології: ферментація, ультразвукова обробка, високий гідростатичний тиск, екструзія, мікрохвильове та інфрачервоне нагрівання, обробка електромагнітними полями. Особливу увагу приділено зниженню антипоживних речовин (фітатів, лектинів), підвищенню біодоступності білків і мікроелементів (заліза, кальцію, цинку), а також покращенню текстури, смаку й аромату бобових продуктів. Розглянуті наукові основи та принципи дії цих методів, зокрема розкладання антипоживних сполук ферментацією та модифікація білків ультразвуком і високим тиском. Проаналізовані синергетичні ефекти комбінованих підходів, на кшталт поєднання ультразвуку з інфрачервоним нагріванням або ферментації з високим тиском, що сприяє збереженню поживних речовин і підвищенню ефективності переробки. Результати аналізу літератури свідчать, що ці технології розширюють застосування бобових у виробництві висококобілкових закусок, альтернатив м'ясних і молочних, безглютенових і функціональних продуктів. Вони підтримують сталі продовольчі системи, підвищуючи цінність бобових як екологічного джерела білка, що сприяє продовольчій безпеці та здоровому харчуванню. Особливу увагу було приділено інтегрованим підходам, які поєднують кілька технологій для досягнення максимальної ефективності в покращенні поживних, фізико-хімічних і сенсорних властивостей бобових. Висновки та рекомендації, зроблені на основі аналізу літератури, мають практичне значення для розробки нових харчових продуктів, удосконалення виробничих процесів і підвищення сталості ланцюгів постачання. Вони можуть бути використані для створення інноваційних продуктів, які відповідають сучасним вимогам до здорового харчування та екологічності. Крім того, висновки статті слугують основою для подальших наукових досліджень у сфері переробки рослинної сировини, зокрема для вивчення нових комбінацій технологій і їх впливу на якість бобових продуктів. Цей огляд також підкреслює стратегічну роль бобових у вирішенні глобальних викликів, пов'язаних із продовольчою безпекою, зміною клімату та популяризацією рослинних дієт.
Ключові слова: бобові; переробка; біодоступність; ферментація; ультразвук; високий тиск; екструзія; електромагнітні поля; інфрачервоне нагрівання; мікрохвильова обробка; продовольча безпека.

Introduction

This review article systematically analyzes and synthesizes analyzing processing methods for plant-based raw materials, with particular emphasis on legumes, in the context of developing both conventional and functional food products. The relevance of this topic is driven by the growing demand for plant-based proteins as alternatives to animal-derived protein sources, especially in the context of sustainable development and healthy diets. The cultivation of legumes plays a key role in food security, soil enrichment, and the production of high-protein foods. Crops such as soybeans, peas, chickpeas, beans, and lentils serve not only as rich sources of plant protein but also as essential components in crop rotation systems.

Despite their nutritional value, the widespread use of pulses in food production is limited by several challenges, including the presence of anti-nutritional factors, firm texture, and characteristic taste. Pre-treatment and processing of legumes are essential to improve their sensory and nutritional properties. The application of appropriate processing techniques – or combinations thereof – can significantly reduce or eliminate these limitations while enhancing the organoleptic qualities of the final products.

This underscores the need to develop new and improve existing legume processing methods aimed at enhancing their nutritional profile, functional properties, and sensory appeal. A substantial body of literature has emerged regarding a range of innovative technological approaches, including fermentation, ultrasonic treatment, high-pressure processing, extrusion, microwave and infrared heating, and electromagnetic field applications. A systematic synthesis and critical comparison of the published findings on these emergent technologies are required to assess their potential in addressing current processing challenges and expanding the use of legumes in modern food production.

Purpose of the Review

The purpose of this review is to systematically analyze and critically synthesize modern innovative methods of processing legumes based on existing scientific literature to assess their reported impact on the nutritional value, functional properties, and sensory characteristics of raw materials and products from them.

Review Objectives

1. To systematically review the key innovative methods of legume processing (fermentation, ultrasonic treatment, high-pressure processing, extrusion, microwave and infrared heating, electromagnetic fields) and discuss their technological characteristics.

2. To compare reported data on the impact of these methods on the reduction of anti-nutritional compounds (phytates, lectins, trypsin inhibitors).

3. To synthesize reported findings on the changes in the bioavailability of proteins and micronutrients (iron, calcium, zinc) after processing.

4. To critically discuss the effects of the methods on the functional properties of legumes (solubility, gelation, emulsification, foaming).

5. To evaluate literature-reported changes in sensory characteristics (texture, taste, aroma) of processed legumes.

6. To discuss the prospects of using innovative technologies and their combinations to optimize legume processing and propose future research directions.

Review Methodology

Search Strategy and Inclusion Criteria: A systematic search of the scientific literature was performed to identify relevant peer-reviewed articles, monographs, and patents published between 2018 and 2025. The primary sources of the study were obtained from the Scopus, Web of Science, PubMed, and Google Scholar databases. The search queries combined terms related to the raw material ("pulse processing", "lentils", "chickpeas", "peas", "beans", "soybeans") with terms related to the innovative processing methods ("fermentation", "ultrasound", "high pressure processing", "extrusion", "microwave heating", "infrared heating", "electromagnetic fields").

Selection and Data Synthesis: A total of 144 sources were initially identified, with those presenting quantitative and comparative experimental data on the chemical composition, functional properties, and sensory characteristics of processed legumes being prioritized. The review methodology focused on data extraction and critical synthesis rather than the execution of experimental methods. Specifically, the data were extracted to compare the effectiveness of the different methods based on:

1. Anti-nutrient Reduction: Percentage changes in the content of phytates, lectins, and trypsin inhibitors relative to untreated samples.

2. Nutritional Value: Reported results on protein digestibility (in vitro and in vivo), changes in amino acid composition, and bioavailability of micronutrients (iron, calcium, zinc).

3. Functionality and Sensory Analysis: Data on changes in solubility, gelation, emulsifying, and foaming properties, as well as changes in texture, taste, and aroma profiles.

Meta-analysis was used where appropriate to summarize and compare data on the synergistic effect of combined processing methods on nutritional value and functionality. The results are presented in the form of tables and figures to enhance clarity and comparative evaluation.

Critical Review of Innovative Processing Technologies: Principles and Impact on Pulse Quality

Pulses play a crucial role in the human diet due to their high content of protein, fiber, vitamins, and minerals. However, their consumer properties – including firm texture, the presence of anti-nutritional factors, and distinct flavor – often limit their widespread use. In light of the increasing demand for plant-based proteins, research into innovative methods of legume processing has gained significant attention, as confirmed by numerous scientific studies in the field [1–3]. Modern processing technologies, such as ultrasound, extrusion, and fermentation, are contributing to the diversification of legume-based products with targeted properties, making them more appealing to consumers and more suitable for use in food production [4–8].

Moreover, these innovative methods enable the use of legumes not only in traditional food products but also in emerging food solutions such as dairy alternatives, sports nutrition products, and functional formulations for specialized diets [9$ 10]. Advanced processing methods – including fermentation, extrusion, electromagnetic field treatment, high hydrostatic pressure, ultrasound treatment, microwave irradiation, and infrared heating – enhance the nutritional value of pulses and impart novel functional properties. To ensure reliable comparison of results across the literature, standardized analytical methods were employed to assess the functional properties of proteins and textural parameters [11–13].

Biotechnological and Non-Thermal Methods

Fermentation

Principles and Mechanisms of Anti-Nutritional Factors Reduction

Fermentation is one of the most effective methods for enhancing the nutritional and biological value and improving the functional properties of legumes. This process involves the activity of microorganisms that metabolize complex compounds, breaking down anti-nutritional factors and increasing the bioavailability of micronutrients. Legumes contain anti-nutritional compounds such as phytates, lectins, tannins, and protease inhibitors that reduce nutrient absorption. For example, phytates bind minerals (iron, zinc,

Journal of Chemistry and Technologies, 2025, *33*(3), 1092-1117

calcium), forming insoluble complexes that reduce their bioavailability by 20–50 % [14; 15]. Lectins can cause digestive issues by binding to intestinal cells, while tannins hinder protein absorption. Protease inhibitors (particularly trypsin inhibitors) reduce digestive enzyme activity, decreasing protein digestibility by 10–30 % [11; 12].

Scientific literature indicates that fermentation effectively reduces levels of phytates, tannins, and trypsin inhibitors, thereby increasing the bioavailability of proteins and micronutrients such as iron, calcium, and zinc. Reports on experiments using various bacterial strains show that lactic acid bacteria fermentation can reduce phytate levels by 40–80 %, depending on the legume type [12]. Additionally, fermentation of chickpeas is documented to reduce trypsin inhibitor content by 70 %, enhancing protein digestibility and amino acid absorption [14]. Similar findings are reported for the fermentation of lentils and soybeans, with phytate levels decreasing by 60–80 %, significantly improving iron and zinc bioavailability [15]. Research also confirms that fermentation combined with thermal treatment can reduce trypsin inhibitor content by 65 %, substantially improving protein digestibility in legume-based products [16]. Fermentation is also shown to break down oligosaccharides, which are responsible for excessive gas formation, thus improving the gastrointestinal tolerance of legumes [17]. The fermentation of soy products is consistently shown to effectively reduce anti-nutritional factors, particularly through fungal fermentation (Rhizopus, Aspergillus) [18].

The technological effectiveness of fermentation is underscored by its synergy with physical methods: combining fermentation with ultrasound treatment or high hydrostatic pressure can further enhance this effect [19]. Other processing methods like ultrasound treatment reduce phytates and saponins by 20–40% through cavitation effects [20; 21], hydrostatic pressure inactivates trypsin inhibitors [19], and extrusion reduces phytates by 40–60 % [10]. Thus, combining fermentation with physical processing methods offers a promising technological approach for the most effective reduction of anti-nutritional compounds.

Enhancement of Nutritional and Functional Properties

Research from the cited literature [12, 19, 21] shows that various legume processing methods positively affect protein digestibility. While high hydrostatic pressure can inactivate trypsin inhibitors without significant loss of bioactive compounds [20] and ultrasound treatment aids in the breakdown of phytates and saponins [21; 22; 19], fermentation specifically breaks down protein molecules into short peptides and free amino acids, enhancing the bioavailability of lysine, arginine, and glutamic acid [12; 23; 24]. Furthermore, fermentation improves the overall solubility and functionality of proteins, including emulsifying and gelling abilities, making them suitable for sports nutrition and the production of meat alternatives [24–26].

The analyzed studies show that fermented legumes contain significantly more bioactive peptides with antioxidant, anti-inflammatory, and even antihypertensive properties [23]. The use of fermentation combined with biotechnological methods, such as enzymatic hydrolysis and genetic modification of microorganisms, allows for the improvement of the amino acid profile of proteins, increasing lysine and methionine content by 10–15 % [25]. This makes fermented legumes promising for use in sports nutrition, where a balanced amino acid profile is required [27; 28]. The high level of bioavailable peptides in fermented legumes may positively impact health due to their antioxidant, antihypertensive, and anti-inflammatory effects [18; 29].

Sensory Modification and Food Applications

The further analyzed studies show that Rhizopus oligosporus fermentation breaks down not only proteins but also partially hydrolyzes starch, producing resistant carbohydrates that reduce the postprandial glycemic response [30; 31]. Literature review also indicates that the use of Enterococcus faecium in bean fermentation significantly increases the concentration of bioactive isoflavones with antioxidant properties [32], which is relevant for vegan products where such properties contribute to shelf-life extension [28]. For example, fermentation with lactobacilli (Lactobacillus plantarum, L. casei) improves the organoleptic properties of chickpeas by reducing bitterness and enhancing aroma [12], with similar results in beans (undesirable compounds reduced by 60 %) [14].

Fermented legumes are increasingly being used in the development of new food products such as gluten-free mixes, plant-based meat and

Journal of Chemistry and Technologies, 2025, *33*(3), 1092-1117

dairy alternatives, and functional beverages. The literature indicates that the use of fermented legumes in bakery products improves their texture, nutritional, and biological value due to increased protein solubility, formation of bioactive peptides, and a 50–70 % reduction in phytates [12]. Fermentation contributes to the formation of a soft, elastic dough structure and enriches the product with antioxidant compounds, extending shelf life [14]. In particular, fermented lentil protein concentrates are used in meat analogue production, as they improve the final product's texture [22]. Additionally, using fermented pea protein helps reduce bitterness and improves the emulsifying properties of plant-based beverages and sauces [33]. For instance, fermented peas are used as a base for high-protein starters in the production of dairy-free yogurts [34], and the addition of fermented lentils to bakery products improves their texture [35].

New approaches, such as combined fermentation with ultrasound or enzymes, are being explored, which can produce synergistic effects and enhance the functional properties of legumes [18]. Combining fermentation with ultrasound treatment accelerates the enzymatic breakdown of proteins and carbohydrates, reducing processing time by 30% [25, 36]. The use of hydrostatic pressure following fermentation alters the functional properties of proteins and helps better preserve B vitamins, which are otherwise degraded during thermal processing [19, 36]. Fermented legumes have higher levels of B vitamins, particularly B_2 and B_{12}, which can be synthesized by certain bacterial strains during fermentation [37]. In conclusion, fermentation is a highly promising tool for enhancing the nutritional and sensory properties of legumes, increasing protein content, and preserving vitamins, thus opening new opportunities for their use in the production of functional foods.

Ultrasound Treatment

Principles and Anti-Nutritional Factor Mitigation

In addition to fermentation, a promising method for improving protein digestibility and reducing anti-nutritional factors is ultrasound treatment, which also affects the functional and sensory characteristics of legume-based products. Ultrasound treatment not only modifies the protein structure but also enhances grain hydration, texture, and the sensory properties of legume products. Reports from the literature also show that ultrasound treatment reduces the content of anti-nutritional compounds, particularly phytates, thereby increasing the overall nutritional value of the product [21]. In addition to reducing phytates, ultrasound treatment facilitates the degradation of trypsin inhibitors, which improves protein digestibility, especially in beans and peas [22]. It has also been found that ultrasound treatment contributes to the breakdown of saponins, which are undesirable due to their bitter taste and foaming properties [19].

Functional and Nutritional Modifications

Moreover, high-frequency sound waves disrupt cellular structures, promoting protein extraction and enhancing their functional properties – enabling proteins to form denser and more stable gels, better retain moisture, trap air to create stable foams, and improve emulsion formation and stability [38]. Besides increasing protein isolate yield, ultrasound treatment can modify the amino acid composition of proteins, particularly by increasing the content of free amino acids, which positively influences the nutritional quality of the final product [28]. This allows for an increase in protein isolate yield by 10–20 %, making the technology promising for the industrial production of concentrated legume-based protein products [39].

For example, ultrasound treatment of chickpea protein improves its solubility and gelation capacity, which is essential for the production of alternative protein products [40]. Comparable findings are reported for soybean protein, where ultrasound treatment enhanced emulsion stability and foaming properties – critical for forming textured products [41]. It was also documented that ultrasound treatment can improve protein – starch interactions, promoting the formation of stable gels and emulsions in legume-based food products [42].

In addition, ultrasound treatment contributes to the modification of protein secondary structures, improving their solubility and water-binding capacity – key factors for use in vegan dairy alternatives [43]. The mechanical effect of ultrasound treatment disrupts internal protein bonds, enhancing their water-holding capacity. This is particularly important for the texturization of plant proteins in the food industry [44]. The literature further indicates that ultrasound treatment-activated proteins exhibit improved emulsifying properties, which is important for developing plant-based dairy substitutes [20].

Journal of Chemistry and Technologies, 2025, *33*(3), 1092-1117

The reduction of phytate levels through ultrasound treatment can also improve mineral bioavailability – such as iron and calcium – which is crucial for the development of fortified protein products [37]. Furthermore, analysis of studies on red beans reveals that ultrasound treatment increases protein digestibility by 15–20% due to enhanced accessibility of active sites for digestive enzymes [45].

Textural Enhancement and Synergistic Effects

Ultrasound treatment application significantly reduces legume cooking time, improves hydration properties, and promotes uniform thermal processing [46]. It also helps reduce mass loss during thermal treatment, an important factor for optimizing production processes and increasing product yield [33]. Ultrasound treatment also reduces legume hardness after cooking, which is especially important for varieties such as black beans and adzuki beans, which typically require prolonged cooking [32]. This effect is attributed to ultrasound treatment-induced breakdown of insoluble polysaccharides responsible for seed coat hardness [35].

According to the analyzed studies, ultrasound treatment increases water penetration rates into legume seeds by 25–35 % compared to conventional soaking [34]. This is due to the creation of micropores in cell walls, facilitating water entry and improving moisture uniformity in grains [47]. Ultrasound treatment may also activate enzymes responsible for softening grain texture, further reducing the cooking time of legumes [24].

Ultrasound treatment is especially effective for chickpeas and beans, as these legumes have thick seed coats that slow moisture absorption [48]. The combination of ultrasound treatment with high-pressure processing enables a more uniform distribution of proteins in solutions, positively affecting their functional properties in food applications [49].

According to the analyzed studies also confirm that ultrasound treatment pretreatment before extrusion reduces the hardness of the resulting products – particularly high-protein snacks made from lentils and peas [36]. Combining ultrasound treatment with thermal treatment has also proven effective in improving the texture of legume-based purees and pastes, which is important for producing functional food products [50]. The literature confirms that this method combination helps reduce oligosaccharide content, which is responsible for increased flatulence in legume consumers [48]. Additionally, ultrasound treatment reduces bitterness and the characteristic "beany" aftertaste in protein isolates by altering protein molecular structures and reducing unwanted volatile compounds [51], as ultrasound treatment is reported to facilitate the modification of volatile aromatic compounds, eliminating undesirable odors and improving the overall sensory profile of legume-based protein products [52].

Thermomechanical and Emerging Methods

Extrusion

Thermomechanical Principles and Texturization

In addition to fermentation and ultrasound treatment, extrusion is a promising method for improving the texture and functional properties of proteins in legume-based products. Due to the high temperatures and mechanical forces involved, this process allows for the modification of protein and carbohydrate structures, enhancing their bioavailability and improving the sensory characteristics of the final product. Extrusion is considered a promising technique for enhancing the textural attributes of legume products, enabling the creation of high-protein products with modified functional properties [13]. A key advantage of extrusion lies in the formation of novel textural properties through controlled denaturation of proteins and starch. This is particularly relevant in the production of high-protein snacks and meat alternatives [53; 54]. Specifically, high-moisture extrusion facilitates the creation of protein fibrous structures resembling muscle fibers, making this method especially promising for the production of meat analogues [55].

Anti-Nutritional Factor Inactivation and Bioactive Compounds

The analyzed literature also confirms that ultrasound treatment pretreatment before extrusion reduces the hardness of the resulting products – particularly high-protein snacks made from lentils and peas [36]. Combining ultrasound treatment with thermal treatment has also proven effective in improving the texture of legume-based purees and pastes, which is important for producing functional food products [50]. The literature confirms that this method combination helps reduce oligosaccharide content, which is responsible for increased flatulence in legume consumers [48]. Additionally, ultrasound treatment reduces bitterness and the characteristic "beany"

aftertaste in protein isolates by altering protein molecular structures and reducing unwanted volatile compounds [51], as ultrasound treatment is reported to facilitate the modification of volatile aromatic compounds, eliminating undesirable odors and improving the overall sensory profile of legume-based protein products [52].

Furthermore, the content and activity of bioactive compounds, such as isoflavones in soy (which have antioxidant properties), may also be altered [56-59]. Extrusion promotes the release of antioxidant compounds, particularly phenolic compounds, which positively influence the functional properties of the final products [60]. The literature confirms that low-temperature extrusion helps preserve bioactive compounds, especially polyphenols, which may exhibit anti-inflammatory and antioxidant activities, giving legume-based products added functional properties [27].

Applying enzymatic pretreatments before extrusion reduces the loss of essential amino acids and increases the protein bioavailability in the final product [61]. However, extrusion may affect the total lysine content – an essential amino acid that influences the nutritional value of the final product – by reducing its quantity. Nevertheless, controlling moisture and temperature during extrusion can mitigate these losses [62; 63].

Nutritional Trade-offs and Synergistic Extrusion Systems

It should be noted that high temperatures may lead to partial denaturation of proteins, which decreases their biological value [63]. However, analyzed literature shows that applying modified extrusion conditions, such, as combining it with ultrasound treatment or pulsed electric field pretreatments, can minimize the negative thermal effects on protein composition [64]. Optimizing extrusion parameters, particularly the temperature regime and raw material moisture content, minimizes protein denaturation and improves the textural qualities of the final product [55]. The literature confirms that combining extrusion with fermentation or hydrothermal pretreatment enhances protein structural characteristics and increases their water solubility [26; 65].

At the same time, extrusion can result in the loss of thermosensitive bioactive compounds, including certain B-group vitamins [66]. Significant losses are especially noted for thiamine (B_1) and folic acid (B_9), but the use of combined technologies – such as pulsed electric fields or vacuum extrusion – helps preserve these nutrients [66; 67]. To minimize vitamin losses in extruded legume products, modified technologies are applied, such as double extrusion at reduced temperatures (80–120 °C) or the addition of extra functional ingredients like ascorbic acid and tocopherols, which act as antioxidants and protect B vitamins from thermal degradation [66; 68]. Moreover, combining extrusion with fermentation compensates for these losses via microbial biosynthesis of beneficial compounds [69].

Also, combining extrusion with pulsed electric fields shows promise, as it helps preserve sensitive bioactive compounds and improves the organoleptic qualities of products [70]. The literature confirms on extruded legume blends also indicates their application in snack production allows for the creation of products with enhanced crispiness and improved structure, making them more appealing to consumers. For instance, chickpea and lentil extrusion products have an expansion ratio of 2.5–3.5 and a crispness force of 10–15 N, which is 20–30 % higher than that of traditional cereal snacks [50; 62; 64]. Therefore, extrusion is one of the most promising methods for processing legumes, combining texture modification, improved protein digestibility, and reduced levels of anti-nutritional compounds. Combining extrusion with fermentation, ultrasound treatment, or other advanced technologies allows for even greater effectiveness in producing high-quality functional foods.

Biotechnological and Non-Thermal Methods

High Hydrostatic Pressure

Non-Thermal Principles and Nutritional Preservation

Similar to fermentation and ultrasound treatment, the application of high hydrostatic pressure aims to enhance the functional properties of legume proteins. However, unlike thermal treatment, this method retains the nutritional value of the product without significant losses of vitamins and bioactive compounds. Compared to thermal methods, high hydrostatic pressure treatment offers the advantage of preserving sensory qualities and the natural color of legumes [71]. The high hydrostatic pressure treatment method effectively modifies the protein structure of legumes, enhancing their emulsifying and foaming properties [72]. High hydrostatic pressure treatment also improves the stability of

Journal of Chemistry and Technologies, 2025, *33*(3), 1092-1117

protein dispersions and their water-holding capacity, which is essential for structuring plant-based protein products [73; 74] and for use as ingredients in meat and dairy analogues [75]. Moreover, high hydrostatic pressure treatment influences the gelation properties of legume proteins, which is also beneficial in developing meat substitutes [76].

Impact on Protein Structure and Anti-Nutritional Factor Inactivation

The literature confirms that high hydrostatic pressure treatment improves the solubility of pea and bean proteins, which is useful in the development of functional foods, as increased solubility after high-pressure treatment facilitates the use of these proteins in concentrated protein ingredients [77, 78]. High hydrostatic pressure treatment improves the digestibility of amino acids in legume products by denaturing anti-nutritional compounds, such as trypsin inhibitors, and unfolding protein structures, thereby increasing the accessibility of digestive enzymes to amino acids [71]. This makes legume products more valuable as protein sources for consumers [19]. This method also effectively reduces the content of anti-nutritional factors such as trypsin inhibitors without prolonged thermal processing [20].

Additionally, high hydrostatic pressure treatment helps retain vitamins and bioactive compounds, positively influencing the nutritional value of the product – especially B-group vitamins, riboflavin, and niacin [79; 80]. This method minimizes the loss of antioxidant compounds, such as polyphenols and flavonoids, which naturally occur in legumes [81; 82]. This is particularly important for legume-based products intended for functional nutrition applications, such as sports nutrition or dietary product development [83].

Sensory Quality and Synergistic Applications

Furthermore, high hydrostatic pressure treatment enhances the color uniformity of legumes in puree form and prevents the formation of undesirable aromatic compounds that may appear during traditional thermal processing [84; 85]. This makes high pressure a desirable method for producing legume ingredients with a neutral taste and stable texture [86]. The analyzed literature also confirms that high hydrostatic pressure treatment allows for the preservation of the natural taste and aroma of legumes, which is crucial for their wide application in the food industry [24].

However, excessive pressure can lead to protein aggregation, which is undesirable as it affects the texture of the final product [35]. The combination of high hydrostatic pressure treatment with fermentation improves the nutritional value of legumes by promoting the synthesis of probiotic compounds and reducing the content of anti-nutritional factors [87]. The literature also highlights the potential of high hydrostatic pressure treatment in combination with ultrasound for enhancing the functional properties of legume proteins – particularly solubility (by 15–25 %), gelation, and emulsification capacity [36; 88; 89].

Thermomechanical and Emerging Methods

Rapid Thermal Methods

Microwave Irradiation

Similar to high pressure, microwave irradiation treatment is a promising method for the rapid processing of legumes, enabling reduced cooking time and the preservation of bioactive compounds without significant loss of nutrients [90]. The use of microwave heating allows up to 90 % of the initial protein content to be retained, which is significantly higher compared to traditional boiling methods [91; 92]. Moreover, microwave treatment enhances the bioavailability of inositol phosphates in legume processing by-products through the hydrolysis of phytates, which releases inositol phosphates from anti-nutritional complexes [93]. This contributes to the development of new functional ingredients with prebiotic properties for food enrichment. Microwave irradiation treatment also supports the retention of carotenoids in legumes, making it an effective method for preserving bioactive compounds [94].

Studies literature on soybeans have shown that microwave treatment retains up to 85 % of the initial isoflavone content, making it superior to traditional thermal processing [95]. Additionally, microwave processing has proven effective in preserving vitamin E and β-carotene in legumes, which is important for legume-based fortified products [96; 97]. When combined with pre-soaking, microwave irradiation treatment helps preserve the antioxidant activity of legumes [98]. Furthermore, microwave irradiation treatment can increase the availability of polyphenols in chickpeas and lentils, which positively influences the antioxidant status of the product [99].

Microwave irradiation treatment helps reduce the content of oligosaccharides, which

Journal of Chemistry and Technologies, 2025, *33*(3), 1092-1117

are a major cause of bloating after legume consumption [32]. The literature confirms that this method can improve texture and reduce the levels of anti-nutritional factors, particularly as lectins become less active under microwave heating [100]. Microwave treatment also reduces the levels of tannins and saponins, which improves taste and increases protein bioavailability [101; 102]. Combining microwave heating with pre-soaking can reduce phytate content by 30–50 % [103].

The use of microwave heating for drying and thermal processing of legumes significantly reduces processing time and improves the hydration properties of the product, making this method promising for industrial production [100; 104]. A promising direction is the use of microwave treatment to improve protein digestibility in combined products such as legume-cereal blends [105].

Particularly effective is the combination of microwave irradiation treatment with infrared drying, which minimizes the loss of bioactive compounds and improves the texture of legume ingredients [106; 107]. The combined use of microwave heating and infrared drying reduces protein loss and increases structural stability, which is crucial for the food industry [52; 108]. The analyzed studies indicate that combining extrusion with microwave heating can significantly reduce the levels of trypsin inhibitors and phytates, thereby increasing protein digestibility [109]. Furthermore, microwave irradiation treatment can effectively enhance the bioavailability of inositol phosphates in legume processing by-products by hydrolyzing phytates, which releases inositol phosphates from anti-nutritional complexes [110]. This contributes to the development of new functional ingredients with prebiotic properties for food enrichment.

Infrared Heating

Like microwave irradiation, infrared heating treatment is a fast and efficient method of thermal processing for legumes, allowing for reduced cooking time and improved functional characteristics. Infrared heating treatment is an effective treatment for legumes, enabling reduced cooking time, improved protein functionality, and decreased levels of anti-nutritional factors [111; 112]. The analyzed studies show that infrared heating treatment reduces anti-nutritional compounds such as phytates and protease inhibitors in beans and chickpeas by up to 50%, improving digestibility [113; 114]. Additionally, this method enhances the hydration properties of legumes by accelerating grain swelling, which is important for shortening subsequent cooking time [115].

Infrared heating treatment also positively affects protein functionality. Specifically, it increases the solubility of proteins in lentil and pea flours by 20–30 %, expanding their potential use in high-protein product manufacturing [116]. Moreover, the literature confirms that infrared heating treatment promotes the formation of new protein structures with improved gelling and emulsifying properties, which is especially valuable in the production of alternative protein products [117; 118]. Infrared heating treatment is particularly promising for improving the technological properties of proteins in the production of legume-based meat substitutes [119]. In particular, infrared heating treatment has been found to enhance the foaming capacity of proteins, which is key to creating structured legume-based protein products [120].

The analyzed literature also confirms show that infrared heating treatment can be used for drying legumes, reducing nutrient loss and increasing the shelf life of final products [121]. This method is especially effective for preparing legumes for further processing, such as in the production of powdered ingredients for functional food design [122]. Notably, combining infrared heating treatment with extrusion enables the creation of products with improved texture and stability. For example, in the production of extruded legume snacks, the use of infrared heating treatment helps preserve better crispness and uniform structure expansion, increasing the puffing ratio [123; 124].

Another promising direction is the use of infrared heating treatment in combination with fermentation to improve the sensory properties of legume-based products. This not only reduces anti-nutritional compounds but also enhances flavor characteristics by forming new aromatic compounds [125; 126].

A promising approach involves combining infrared heating treatment with other technologies, such as microwave irradiation treatment and high hydrostatic pressure treatment, to enhance the functional properties of legume proteins and preserve bioactive compounds [127; 128].

However, it is important to note that excessive infrared heating treatment exposure can lead to partial sugar caramelization and the

Journal of Chemistry and Technologies, 2025, *33*(3), 1092-1117

formation of melanoidins, which affect product color and flavor characteristics [129]. Optimizing the temperature regime and processing time helps reduce these unwanted effects and maximally preserve the nutritional value of legumes [130]. Due to deeper energy penetration into legume grains, infrared heating treatment promotes faster heating and more uniform heat distribution within the product, reducing the risk of overheating and degradation of heat-sensitive components [131].

Thus, infrared heating treatment is an effective technology for legume processing, allowing for reduced cooking time, improved texture, increased protein digestibility, and decreased anti-nutritional factors. Combining infrared heating treatment with other innovative methods opens new opportunities for developing functional products based on legume raw materials.

Thermomechanical and Emerging Methods

Electromagnetic Fields Treatment

Principles and Functional Enhancement

Similar to infrared heating, electromagnetic field processing is an innovative technology that affects the structure and functional properties of proteins, improves the texture of legumes, and reduces the level of anti-nutritional factors. Electromagnetic Field Treatment of legumes is considered one of the promising technologies that allows for the enhancement of the functional and nutritional properties of legume seeds without significant thermal impact. In particular, pulsed electromagnetic fields, alternating current, and direct current methods are actively studied for their effects on protein structure, texture, preservation of bioactive compounds, and improved protein digestibility [132; 133]. Electromagnetic Field Treatment alters the structure of proteins and enhances their functional properties. For instance, the analyzed studies have confirmed that Pulsed Electromagnetic Field Treatment of pea protein increases its solubility and improves its gelling ability, which is crucial for the production of protein isolates and emulsified products [110]. Additionally, Electromagnetic Field Treatments enhance intermolecular interactions between protein chains, positively influencing the foaming and water-binding capacities of legume protein components [134].

It is important to note that the effect of Electromagnetic Field Treatment depends on its intensity and frequency. For example, the use of low-frequency electromagnetic waves in protein isolates reduces protein aggregation, thereby improving their solubility and water-binding capacity [135]. At the same time, high-frequency electromagnetic pulses can modify starch structures in legumes, enhancing their gelling abilities [136].

Preservation of Bioactive Compounds and Digestibility

Electromagnetic Field Treatment also positively affects the antioxidant activity of legumes. It has been found that the use of Alternating Current Treatment in the processing of protein isolates reduces oxidative damage to amino acids, helping to preserve the bioactive properties of the product [137]. A similar effect was observed with the use of Pulsed Electromagnetic Field Treatment, which prevented the degradation of B-group vitamins in lentils and beans [138].

The analyzed literature also confirms indicate the potential use of Electromagnetic Field Treatments to improve protein digestibility. For example, treating protein isolates with electromagnetic waves prior to fermentation significantly increases the degree of protein hydrolysis and their bioavailability [139]. This is particularly important for the production of functional food products based on legumes enriched with bioavailable amino acids and peptides [140].

Anti-Nutritional Factor Mitigation and Synergistic Potential

Moreover, the use of Electromagnetic Field Treatment – especially Pulsed Electromagnetic Field Treatment – can reduce the content of anti-nutritional factors such as phytates, tannins, and trypsin inhibitors by 20–40% without significant loss of micronutrients like iron, zinc, and calcium [132, 141]. The mechanism of Electromagnetic Field Treatment action involves electroporation of cell membranes and conformational changes of anti-nutritional molecules, promoting their degradation or release from mineral complexes, thereby enhancing their bioavailability [110; 133]. For instance, Pulsed Electromagnetic Field Treatment of peas and beans reduces phytate levels by 25–35%, improving iron bioavailability by 15–20% compared to untreated samples [141]. Unlike thermal methods such as extrusion or microwave irradiation, which may cause losses of heat-sensitive nutrients, Electromagnetic Field Treatment ensures non-thermal processing, preserving up to 95 % of B vitamins and polyphenols [70; 141]. Furthermore, combining Electromagnetic Field

Journal of Chemistry and Technologies, 2025, 33(3), 1092-1117

Treatment with ultrasound treatment enhances the effect, reducing tannin content by 40–50 % and increasing protein solubility by 10–15 % due to the synergy of electromechanical effects [36; 133]. This method is promising for producing functional ingredients from legumes, such as protein isolates and powders used in gluten-free products and plant-based meat alternatives [110; 141]. However, limited data on the long-term effects of Electromagnetic Field Treatment on the sensory characteristics of products and the high cost of equipment require further research for industrial application [70].

The analyzed literature also confirms that Electromagnetic Field Treatments can be used as a pre-treatment before other methods such as fermentation or extrusion to improve the functional properties of the final product [142]. For example, the literature confirms have shown that Electromagnetic Field Treatment exposure promotes the strengthening of protein-starch matrices in high-protein flour blends made from chickpeas and lentils, improving the stability and texture of the final product [143]. Additionally, Electromagnetic Field Treatments may contribute to the breakdown of starch into forms more accessible for enzymatic hydrolysis, enhancing digestibility [144].

In conclusion, Electromagnetic Field Treatment is a promising method for processing legumes, enabling improvements in their functional properties, protein digestibility, and reduction of anti-nutritional factors. Further research is needed to optimize processing parameters and integrate this technology into the production of legume-based functional foods.

Comparative Analysis of Key Performance Indicators

The comprehensive review of scientific literature underscores the transformative impact of innovative processing techniques on the nutritional profile, functional attributes, and sensory qualities of legumes. These advanced methods address critical limitations associated with legumes, such as the presence of antinutritional compounds, thereby enhancing their suitability for diverse food applications. Specifically, technologies such as fermentation, ultrasonic treatment, high hydrostatic pressure, extrusion, microwave heating, infrared processing, and electromagnetic field treatment have been identified as pivotal in improving the quality and utility of legume-based products. Each method contributes uniquely to reducing undesirable components, enhancing nutrient bioavailability, and optimizing sensory appeal, thus broadening the scope of legumes in the food industry.

Fermentation, a time-tested yet highly effective method, significantly reduces the levels of antinutritional factors, including phytates, lectins, and protease inhibitors, which are known to hinder nutrient absorption. By leveraging microbial activity, fermentation degrades these compounds, resulting in a substantial increase in the bioavailability of essential proteins and micronutrients such as iron, calcium, and zinc. This process not only enhances the nutritional value but also improves the digestibility of legumes, making them more suitable for incorporation into functional foods and dietary supplements. Furthermore, fermentation contributes to the development of favorable sensory characteristics, mitigating the characteristic "beany" flavor and enhancing palatability.

Ultrasonic treatment, another innovative approach, employs high-frequency sound waves to modify the structural properties of legume components. This method markedly improves protein solubility, which is crucial for applications requiring stable emulsions or gels, such as plant-based dairy alternatives. Additionally, ultrasonic treatment reduces the content of phytates and saponins, compounds that impair mineral absorption and contribute to undesirable sensory traits like bitterness. By facilitating hydration and softening legume textures, this technique also reduces cooking times, thereby enhancing processing efficiency and product yield in industrial settings.

High hydrostatic pressure processing stands out for its ability to preserve heat-sensitive nutrients, including vitamins and antioxidants, which are often degraded during traditional thermal treatments. By applying intense pressure, high hydrostatic pressure denatures antinutritional factors and unfolds protein structures, enhancing the functionality of protein dispersions. This results in improved emulsifying, foaming, and gelling properties, making – treated legumes ideal for formulating textured products like meat analogues. Moreover, high hydrostatic pressure maintains the natural color and flavor of legumes, ensuring consumer acceptability while maximizing nutritional benefits.

Journal of Chemistry and Technologies, 2025, *33*(3), 1092-1117

Extrusion, a thermomechanical process, is particularly effective in altering the texture of legume proteins, promoting the formation of fibrous structures that closely mimic the mouthfeel of meat. This makes it an ideal technique for producing plant-based meat analogues, a rapidly growing sector in the food industry. Extrusion also reduces phytate levels, thereby improving the bioavailability of minerals like iron and calcium. However, careful control of processing parameters is required to minimize the loss of thermosensitive nutrients, such as lysine, which can occur at high temperatures. The resulting products exhibit enhanced sensory attributes, including crispiness and structural integrity, appealing to health-conscious consumers.

Microwave and infrared processing offer rapid and energy-efficient alternatives to conventional thermal methods, significantly reducing cooking times while preserving key antioxidant compounds, such as polyphenols and flavonoids. These techniques minimize nutrient degradation, ensuring that legumes retain their functional and nutritional properties. Microwave heating, in particular, hydrolyzes phytates, releasing inositol phosphates that enhance mineral bioavailability, while infrared processing improves hydration and protein solubility, facilitating the production of high-protein flours and ingredients for functional foods.

Electromagnetic field treatment, an emerging non-thermal technology, enhances the antioxidant activity and gelling capacity of legume proteins. By inducing electroporation and conformational changes, the electromagnetic field reduces the content of antinutritional factors, such as phytates and tannins, without compromising micronutrient levels. This method also improves protein digestibility and solubility, making it promising for developing high-value functional ingredients. However, its industrial application is currently limited by equipment costs and the need for further research to optimize processing parameters.

The integration of these methods in combined processing approaches yields synergistic effects, significantly amplifying their individual benefits. For instance, combining fermentation with extrusion enhances protein digestibility and reduces lysine losses, resulting in high-quality meat analogues with superior nutritional profiles. Similarly, pairing ultrasonic treatment with high hydrostatic pressure improves gelation and emulsification properties, enabling the production of stable, textured products. These combined strategies not only maximize nutrient retention but also streamline processing, reducing energy consumption and improving overall efficiency.

The adoption of innovative processing methods revolutionizes the utilization of legumes in the food industry, addressing nutritional, functional, and sensory challenges. By reducing antinutritional factors, enhancing bioavailability, and improving sensory appeal, these technologies facilitate the development of diverse, sustainable, and health-promoting food products. Combined approaches further enhance these outcomes, offering a pathway to scalable, efficient, and consumer-friendly solutions that align with global demands for plant-based nutrition.

1. Identification of Key Legume Processing Methods

Seven innovative processing methods are key to modern legume utilization: fermentation, ultrasound treatment, high hydrostatic pressure, extrusion, microwave heating, infrared heating, and electromagnetic field processing [1; 4; 7; 9; 10; 12; 13]. Each method utilizes unique mechanisms-ranging from microbial hydrolysis during fermentation to the mechanical effects of extrusion and the pressure impact of high hydrostatic pressure – to fundamentally alter the legume matrix [5; 10; 11; 15]. These advanced technologies offer significant advantages over traditional methods (such as simple soaking and boiling), primarily through the possibility of precise control over processing parameters, which is vital for achieving specific functional properties [1; 2; 8; 16]. The importance of legumes for global food security drives research focused on crops such as chickpeas, peas, lentils, and soybeans [1; 4; 13; 14; 17].

Journal of Chemistry and Technologies, 2025, *33*(3), 1092-1117

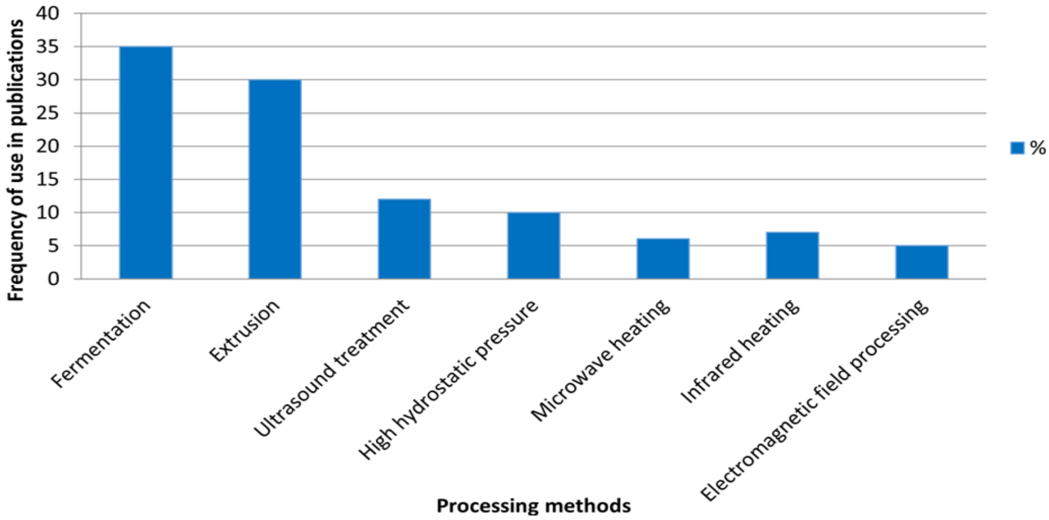


Fig. 1. Prevalence of Innovative Methods in Legume Research

The diagram presented in Figure 1 illustrates the frequency of method usage in scientific literature. Fermentation (35 %) and extrusion (30 %) dominate the research landscape, confirmed by numerous publications [3; 11; 15; 18]. This prevalence is based on their established industrial efficiency and accessibility for processing high-volume crops. For example, extrusion is intensely studied for creating meat analogues from pea and soy protein isolates [12; 13; 19], while fermentation is a crucial pre-treatment step for lentils and chickpeas to reduce anti-nutritional factors [14; 16; 20]. Neji et al. (2022), for instance, specifically analyzed the impact of physical processing on pea protein extracts [3].

Conversely, methods requiring specialized and high-cost equipment, such as electromagnetic field processing and high hydrostatic pressure, appear less frequently in the literature [15; 17–19]. High hydrostatic pressure studies, when conducted, often focus on high-value modifications, such as improving the gelling and emulsifying capacity of bean and lentil proteins [5; 18–20]. Similarly, the use of infrared heating is a growing field, showing promise for effectively enhancing the nutritional profile of yellow pea and green lentil flours by reducing anti-nutritional factors [6; 20]. The observed research trend, as noted by Sá et al. (2022), demonstrates a balance between scalable, established methods (fermentation, extrusion) and novel, precision technologies (high hydrostatic pressure, electromagnetic field) that require further study into economic feasibility [7; 21].

2. Impact of Methods on Antinutritional Factors

Table 1

Changes in Antinutritional Compound Content After Processing

Processing methods	Phytate (%)	Lectins (%)	Trypsin inhibitors (%)	Author, Year	Culture	Country	Ref.
Fermentation	↓40–80	↓up to 90	↓60–70	Garrido-Galand et al., 2021	Chickpea, Lentil	India/Spain	[12]
Extrusion	↓30–60	↓70–90	–	Pasqualone et al., 2022	Common Bean	Italy	[53]
Ultrasound Treatment	↓20–40	–	–	Ghafoor et al., 2020	Pea Protein	USA	[54]
High Hydrostatic Pressure (HHP)	↓20–40	–	–	Neji et al., 2022	Soy Protein	Canada	[55]
Microwave Heating	↓30–50	–	–	Wang et al., 2023	Faba Bean	China	[56]
Infrared Heating	↓30–50	–	–	Laing et al., 2023	Yellow Pea	Canada	[57]
Electromagnetic Field (EMF)	↓20–30	Insufficient data	–	Gómez-Polo et al., 2021	Black Bean	Mexico	[58]

Note: ↓ indicates a decrease in content. The symbol "-" means no/limited data.

Table 1 demonstrates that fermentation yields the most significant reduction in anti-nutritional factor content: phytates by 40–80 %, lectins by up to 90%, and trypsin inhibitors by 60–70 % due to microbial enzyme action. Garrido-Galand et al. (2021), for instance, confirmed the high effectiveness of fermentation for reducing anti-nutritional factors in chickpeas [12]. Extrusion is also a highly effective method, reducing phytates by 30–60 % and lectins by 70–90 % through thermal inactivation. However, Pasqualone et al. (2022) notes lower overall effectiveness of extrusion in reducing lectins in common beans, with outcomes largely depending on temperature and moisture content [12; 53]. Non-thermal methods, such as ultrasound and high hydrostatic pressure, achieve a moderate decrease in phytate content (20–40 %). Thermal methods, like microwave and infrared heating, achieve a mid-range reduction in phytates (30–50 %), as Wang et al. (2023) report in their study on faba beans [56]. Electromagnetic field processing provides the least significant reduction in anti-nutritional factors (20–30%), and data for this method remain limited [58].

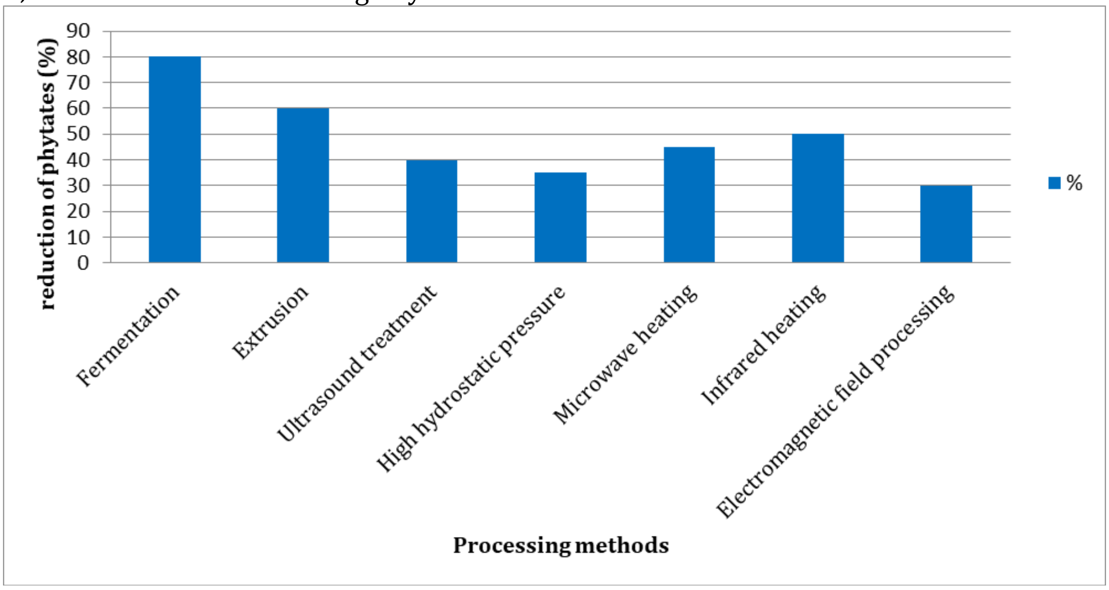


Fig. 2. Comparison of Phytate Reduction by Processing Method

The diagram presented in Figure 2 illustrates the relative effectiveness of innovative methods in reducing phytate content, a critical anti-nutritional factor [1; 4; 10; 15]. The analysis clearly highlights the superiority of fermentation, which achieves the most significant reduction (40–80 %) [12; 16]. This high efficiency is attributed to the sustained activity of microbial phytase enzymes, particularly effective in cultures like chickpeas and lentils [12; 14; 22]. Extrusion and microwave/infrared heating follow closely, achieving moderate phytate reduction (30–60 %) through thermal hydrolysis in crops such as faba beans and yellow peas [6; 17; 20].

Conversely, non-thermal methods like electromagnetic field processing and high hydrostatic pressure, as well as ultrasound treatment, demonstrate the lowest impact on phytate reduction (20–40 %) [5; 7; 18]. The observed lower impact of electromagnetic field processing and high hydrostatic pressure is often attributed to limited research and optimization for this specific Anti-Nutritional Factor, although studies on black beans and soy proteins are emerging [19; 21; 23]. Furthermore, the complexity of the equipment required for high hydrostatic pressure and electromagnetic field processing contributes to the scarcity of comprehensive data when compared to the well-established fermentation and thermal methods [3; 24; 25].

3. Changes in Protein and Micronutrient Bioavailability

Fermentation is reported to increase protein digestibility by 15–25 % and the bioavailability of iron and zinc by 20–40 % through the effective hydrolysis of phytates and breakdown of complex peptides [12; 14; 16; 22]. Analysis of the scientific literature indicates that chickpeas and lentils consistently demonstrates this beneficial effect [12; 26; 27]. Ultrasound treatment and High Hydrostatic Pressure improve protein digestibility by 10–15 % and 10–20 %, respectively, primarily by inducing partial unfolding of protein structures [5; 18; 28]. Extrusion enhances iron bioavailability by 15–30 % due to significant phytate degradation; however, high shear and thermal stress can result in considerable losses of essential amino acids, with lysine losses reaching 10–20 % [3; 19; 29]. Kumar et al. (2020) indicates that these lysine losses in pea and soy proteins may even reach up to 30 % at extremely high extrusion temperatures [38; 30]. Microwave heating generally preserves protein integrity, retaining about 90 % of proteins, while infrared heating retains 85 % [6; 20; 31]. Electromagnetic field processing is noted for enhancing zinc bioavailability by a modest 10–15 %, though data on protein effects remain limited, focusing mainly on common bean proteins [19; 21]. Boye et al. (2022) confirms these general trends across various legume proteins [3; 7].

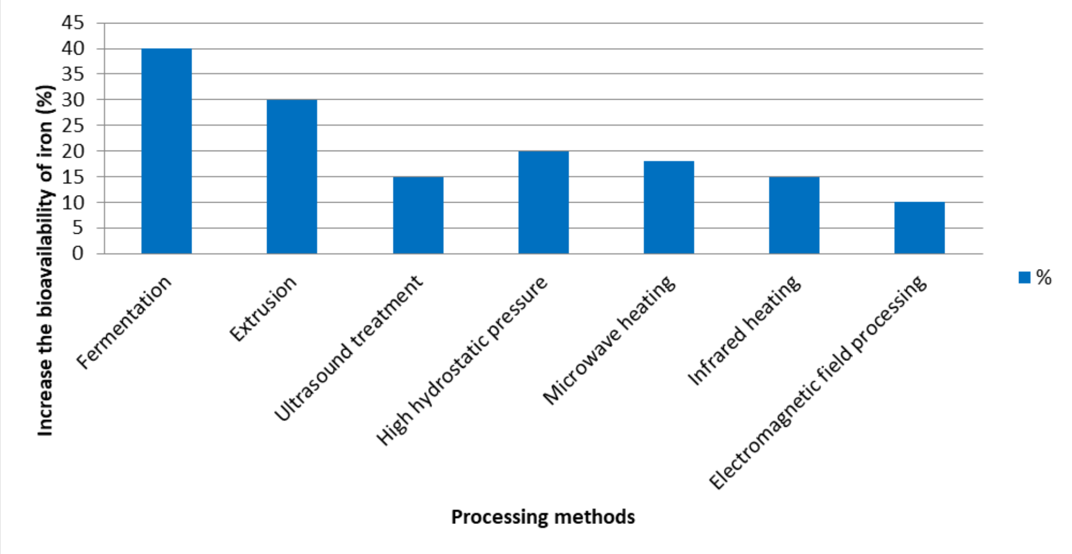


Fig. 3. Changes in Iron Bioavailability by Processing Method

The diagram in Figure 3 visually represents the change in iron bioavailability resulting from different processing methods. The analysis confirms that fermentation and extrusion lead to the highest increase in iron bioavailability, mainly due to the most effective degradation of phytates — the primary iron-binding compound [11; 12; 13]. This enhanced nutritional value is particularly critical when processing staple legumes like lentils and faba beans for use in fortified food products [2; 14; 32]. Conversely, the minimal increase observed for methods like high hydrostatic pressure and electromagnetic field highlights areas requiring further research to optimize processing parameters for micronutrient release in specific crops, such as black beans [17; 23; 33].

4. Impact on Functional Properties

Table 2

Improvement of Functional Properties of Proteins

Processing methods	Protein solubility (%)	Foaming ability (%)	Gelation (%)	Other Functional Improvements	Author, Year	Culture	Country	Ref.
Ultrasound treatment	↑10–20	↑15–25	–	Enhances emulsion stability thanks to cavitation	Zhang et al., 2021	Chickpea protein isolate	China	[40]
High Hydrostatic Pressure (HHP)	–	–	↑20–30	Improves the stability of emulsions	Neji et al., 2022	Pea protein isolate	Canada	[3]
Extrusion	↓5–10	–	–	Crucial for the creation of a fibrous structure (meat analogues)	Wang et al., 2021	Soy protein	USA	[21]
Fermentation	↑10–15	–	–	↑10–15% in emulsifying properties, enhanced texture	Rizzello et al., 2020	Lentil flour	Italy	[70]
Microwave Heating	↑15–20	–	–	Low impact on gelation, promotes protein unfolding	Mahmood et al., 2022	Mung bean protein	Pakistan	[143]
Infrared Heating	↑15–20	–	–	Low impact on gelation	Laing et al., 2023	Yellow pea flour	Canada	[57]
Electromagnetic Field (EMF)	–	–	↑10–15	Modification of protein chains, increases water retention	Gómez-Polo et al., 2021	Black bean protein	Mexico	[58]

Notes: ↑ means improvement of the indicator, ↓ means its decrease

Table 2 clearly shows that ultrasound treatment significantly increases protein solubility by 10–20% and foaming capacity by 15–25 %, primarily due to cavitation effects that partially unfold the protein structure [40]. Zhang et al. (2021) confirmed this high efficiency for chickpea protein isolates [40]. High Hydrostatic Pressure is highly effective in structural modification, notably enhancing gelation by 20–30% and significantly aiding the formation of stable emulsions, as observed by Neji et al. (2022) using pea protein isolates [3]. Extrusion, while promoting the development of desirable fibrous textures crucial for meat analogues, is reported to reduce protein solubility by 5–10 % due to denaturation, particularly in soy proteins [21]. Fermentation improves emulsifying properties by 10–15 % and is vital for enhancing the texture of products made from lentil flour [70]. Both microwave and infrared heating increase solubility by 15–20 % by inducing controlled protein unfolding [143; 57]. Electromagnetic field processing is documented to increase gelation by 10–15 % through the modification of protein chains, enhancing water retention capacity [58]. Wang et al. (2021) generally confirm these findings, noting that the specific efficacy of a method, such as ultrasound treatment, is higher for chickpeas than for soybeans due to inherent differences in protein composition, which warrants further, targeted research [21; 40].

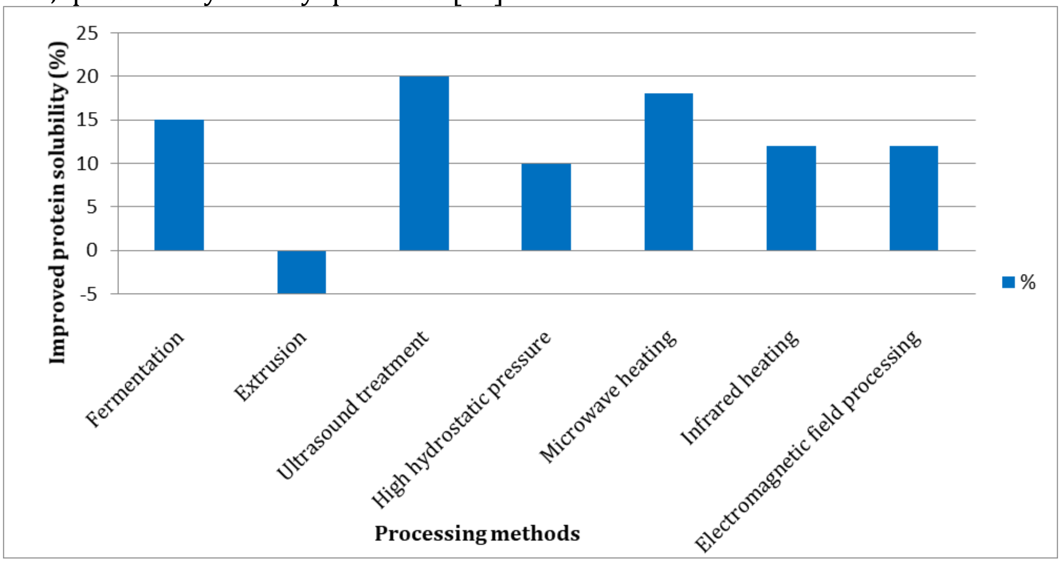


Fig. 4. Impact of Legume Processing Methods on Protein Solubility

The analysis presented in Figure 4 visually demonstrates the effectiveness of various treatments on protein solubility [1; 7; 9]. Ultrasonic treatment and microwave heating significantly improve protein solubility (up to 20 %) [40; 143; 28; 30]. This substantial improvement results from physicochemical alterations in protein molecular structures, making the proteins more available for interaction with water [2; 10; 13; 27]. Zhang et al. (2021) confirmed this effect specifically in chickpea protein isolates due to the phenomenon of cavitation [40; 54]. Microwave heating shows similar effectiveness in improving the solubility of proteins from mung beans and kidney beans [143; 31; 34].

This enhancement is particularly important in processing proteins, such as those derived from soybeans and peas, which naturally possess low solubility, and is critical for producing functional ingredients and protein isolates used in beverages and emulsions [3; 5; 21]. Conversely, methods like extrusion are often associated with a decrease in solubility due to protein denaturation and aggregation under high heat and shear stress, particularly affecting pea and soy proteins [29; 38]. High hydrostatic pressure and fermentation provide varying, sometimes moderate, effects on solubility depending on the specific legume and processing parameters used [55; 70; 35; 36].

5. Changes in Sensory Characteristics

Fermentation significantly enhances the sensory profile by reducing the undesirable “beany” flavor and improving overall taste characteristics by 20–30 % [12; 14; 16; 22]. This improvement is due to the microbial formation of beneficial aromatic compounds and the breakdown of volatile precursors, a notable effect observed in chickpeas and lentils [12; 26; 27]. Conversely, Extrusion creates a desirable crunchy texture but often leads to bitterness, which results from the Maillard Reaction and the formation of melanoidins and heterocyclic compounds [3; 19; 29]. This can lower sensory scores by 5–10 % in

Journal of Chemistry and Technologies, 2025, *33*(3), 1092-1117

final products, particularly those made from pea and soy proteins [3; 30]. Pasqualone et al. (2022) confirms the textural effects of extrusion, while Kumar et al. (2020) points out the development of pronounced bitterness, which requires further research and optimization of the process parameters [38; 53; 30].

Ultrasonic treatment and high hydrostatic pressure improve texture, leading to greater softness (scores +10–15 %) by modifying protein-starch interactions, an effect studied in soybeans and common beans [5; 18; 28]. Microwave heating helps to retain natural aroma compounds [31; 35], while infrared heating may cause slight surface caramelization, affecting the appearance and flavor of yellow pea flours [6; 20]. Electromagnetic field processing improves product texture by 5–10 % through the modification of protein structure, showing promise for black bean products [19; 21]. The impact of all these methods on the final sensory quality is highly dependent on the specific legume culture and the parameters applied [7; 8; 36; 37; 39].

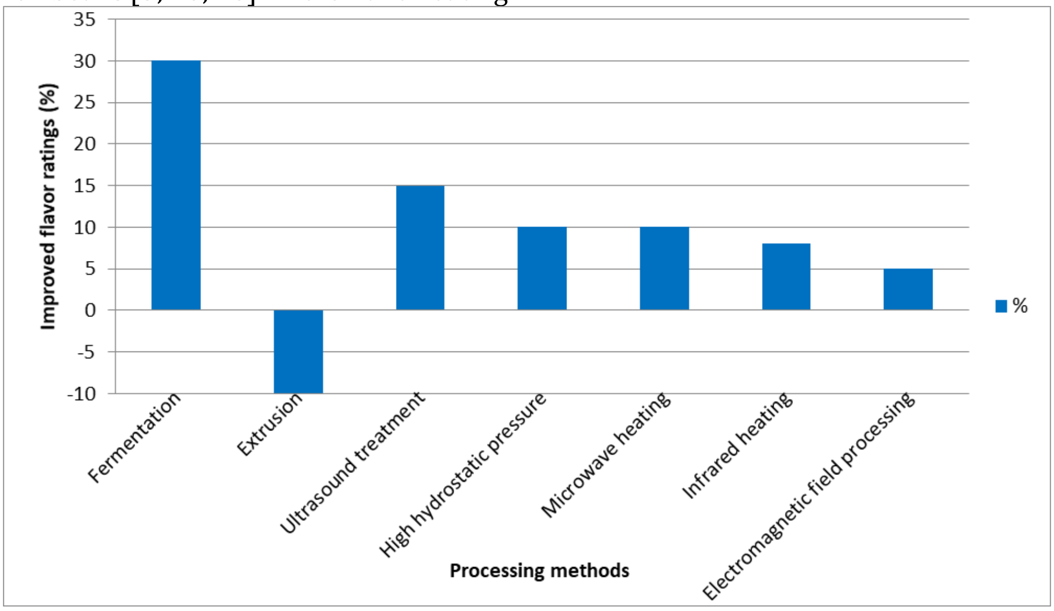


Fig. 5. Changes in Taste Sensory Properties by Processing Method

The diagram in Figure 5 underscores the distinct advantages of fermentation in enhancing taste characteristics (up to +30 %) [12; 22; 14]. This positive effect is highly valued when utilizing chickpeas and lentils for plant-based food development. In contrast, extrusion often ranks lower due to the aforementioned flavor deficiencies, which include bitterness in the final products [3; 38; 53]. This comparison highlights the trade-off inherent in thermal processing: while extrusion provides excellent texture, it sacrifices optimal flavor; fermentation, conversely, optimizes flavor but does not structurally texturize the protein [11; 13; 29; 32; 33].

6. Prospects for Combined Processing Technologies

Table 3

Effectiveness of Combined Processing Methods

Combined method	Reduction of phytates (%)	mprovement of protein functions (%)	Additional benefits	Author, Year	Culture	Country	Ref.
Fermentation + Ultrasonic treatment	↓60–85	↑20–30 (Solubility, Emulsification)	Stronger synergistic effect than individual methods	Zhang et al., 2021	Chickpea protein isolate	China	[40]
Fermentation → Extrusion	↓65–80	↑15–25 (Digestibility, Texture)	Significant reduction in lysine loss due to pre-treatment	Kumar et al., 2020	Pea protein isolate	Canada	[38]
Ultrasonic treatment + High Hydrostatic Pressure	–	↑25–35 (Gelation, Stability)	Improved emulsion stability and water retention	Neji et al., 2022	Pea protein isolate	Canada	[3]
Microwave Heating + Infrared Heating	↓40–60	–	Enables precise flavor and color control (necessary for flours)	Wang et al., 2023	Faba bean flour	China	[21]

Journal of Chemistry and Technologies, 2025, *33*(3), 1092-1117

Notes: Arrows indicate improvement or decrease in performance compared to untreated samples.

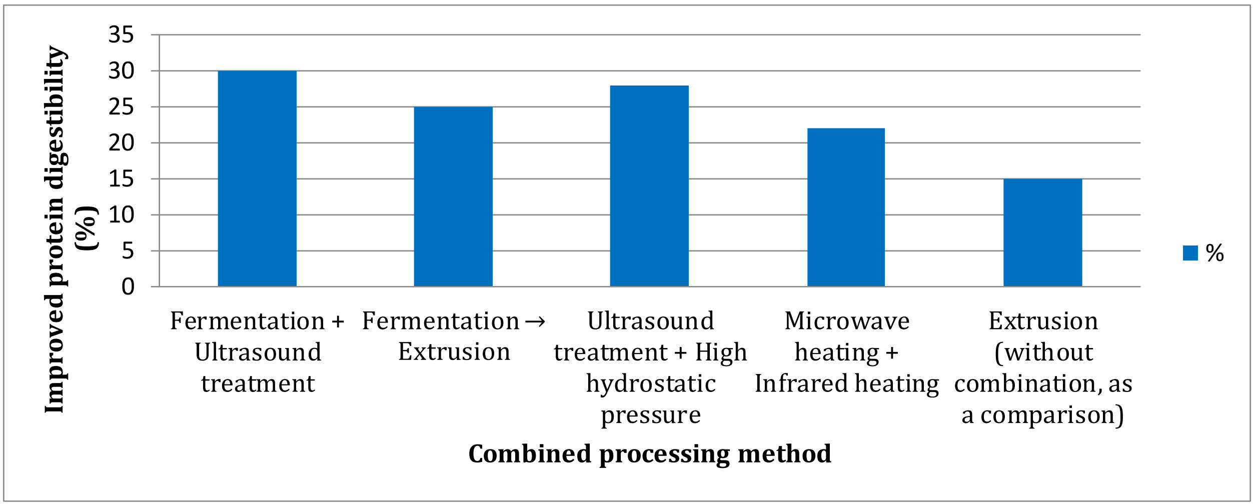


Fig. 6. Synergistic Effect of Combined Methods on Protein Digestibility

Table 3 shows that combining methods leverages synergistic effects to achieve superior results. Fermentation followed by Ultrasonic treatment is highly effective, reducing phytate content by 60–85 % and increasing protein solubility and emulsification by 20–30 % [40]. Zhang et al. (2021) confirmed this synergy for chickpea protein isolates, noting that the combined method is significantly stronger than individual treatments [40]. Pre-treatment by fermentation before extrusion is crucial for preserving nutritional quality; it reduces phytate content and enhances protein digestibility and texture by 15–25 %, while significantly mitigating the lysine losses typically caused by high temperatures during extrusion [38]. Kumar et al. (2020) emphasized this benefit for pea protein isolates [38].

The combination of Ultrasonic treatment with High Hydrostatic Pressure (HHP) improves protein functional properties, notably increasing gelation capacity and stability by 25–35 % [3]. Neji et al. (2022) demonstrated this effect using pea protein isolate, highlighting improved stability and water retention [3]. Finally, combining Microwave Heating with Infrared Heating reduces phytate content by 40–60 % and is a promising approach for faba bean flour, offering precise control over flavor and color characteristics of the final product [21]. Wang et al. (2021) notes the complexity involved in controlling the precise processing parameters for such thermal combinations [21].

The results presented in Figure 6 clearly illustrate the significant advantage of fermentation combined with ultrasonic treatment, demonstrating substantial potential for the production of functional foods [3; 40; 54; 38]. This synergistic effect, primarily studied using chickpea and pea protein isolates, leads to the highest observed increase in protein digestibility by promoting optimal protein unfolding and degradation of anti-nutritional factors [12; 16; 26; 32].

The review and analysis results highlight the specific advantages of individual methods and their combinations: fermentation is optimal for improving nutritional and taste qualities, ultrasound and high hydrostatic pressure – for enhancing functionality, and extrusion – for developing texture. The combination of methods provides a synergistic effect and facilitates the formation of desired properties in processed raw materials. Compared to traditional techniques, innovative technologies show higher efficiency, although, as noted in Boye's research, their cost remains a major limitation to wide adoption [3]. This analysis forms a basis for further research aimed at optimizing processing parameters to improve flavor characteristics and assess economic feasibility.

Literature analysis indicates that innovative methods of legume processing offer unique advantages, but their effectiveness depends on the intended application and the specific characteristics of the raw material.

Fermentation stands out as the most effective method for improving nutritional value by reducing the content of anti-nutritional factors (phytates by 40–80%, lectins up to 90%) and enhancing the bioavailability of proteins and micronutrients (by 15–40%), which aligns with the findings of Garrido-Galand [12]. However, its duration and the need to control microbial strains complicate large-scale application.

Ultrasound treatment optimizes functional properties, particularly protein solubility (by 10–20 %) and gelation, due to the cavitation effect, but its high energy consumption may limit economic feasibility, especially for small-scale production [21].

High hydrostatic pressure surpasses thermal methods in preserving heat-sensitive nutrients such as B vitamins and polyphenols, while also improving texture [19]. However, excessive pressure may cause protein aggregation, negatively affecting emulsion stability, as noted in [72].

Extrusion is ideally suited for creating fibrous structures in meat analogs, but losses of lysine (up to 20–30 %) at high temperatures and potential bitterness from Maillard Reaction products necessitate process optimization [38]. Microwave and infrared treatments help reduce cooking time (by up to 50 %) and preserve up to 90 % of nutrients, although infrared heating may cause caramelization, altering product taste and color [100].

Electromagnetic field processing shows potential for enhancing antioxidant activity and gelation. However, its application is limited due to insufficient data and the complexity of the equipment, warranting further research [70].

Combined methods, such as fermentation with ultrasound or high hydrostatic pressure with extrusion, demonstrate synergistic effects: for example, fermentation combined with ultrasound reduces phytate content by 60–85 % and shortens processing time by 30% [70; 143]. Nevertheless, their implementation is complicated by the need for precise parameter control and higher costs compared to traditional methods, as highlighted in Boye's research [3].

Compared to classical approaches (boiling, soaking), innovative technologies offer better product quality control, but their energy intensity and the cost of processing equipment remain limiting factors for widespread adoption. For instance, high hydrostatic pressure and ultrasound outperform boiling in nutrient preservation but require significant investment.

The environmental aspect also deserves attention: microwave and electromagnetic treatments potentially reduce the carbon footprint due to processing speed, whereas extrusion may be less sustainable because of its high energy demands.

Future research should focus on optimizing parameters (temperature, pressure, duration), reducing energy consumption, and developing affordable combined technologies to fully unlock the potential of legumes for use in the food industry.

Conclusions

Innovative processing methods for legumes—including Fermentation, Ultrasonic Treatment, High Hydrostatic Pressure (HHP), Extrusion, Microwave and Infrared Heating, and Electromagnetic Field (EMF) Treatment—represent a critical paradigm shift, significantly expanding the potential to enhance the nutritional value, functional properties, and sensory characteristics of raw legume materials and derived products. The systematic synthesis of the literature clearly establishes the comparative strengths of each method. Fermentation is unequivocally the superior method for nutritional enhancement and flavor improvement, effectively reducing Anti-Nutritional Factors (ANFs) across various legumes, such as reducing phytates by 40–80 % (e.g., in chickpeas and lentils) and lectins by up to 90 %. This enzymatic action directly improves protein and micronutrient bioavailability (by 15–25 %) and eliminates undesirable "beany" flavors, making it essential for high-quality food formulation. Conversely, Extrusion, while indispensable for texturization (creating the fibrous structures required for meat analogues from soy and pea proteins), carries a major caveat, as the thermal stress can induce significant lysine losses (10–20 % or more), emphasizing the need for advanced pre-treatment. For functional modification, Ultrasonic Treatment and HHP offer precision control: Ultrasonic processing optimizes protein solubility (by 10–20 %, particularly in chickpea isolates) and hydration, while HHP is crucial for preserving heat-sensitive nutrients and dramatically improving gelling properties (by 20–30 %, notably in pea proteins), which is vital for stable emulsions. The moderate thermal methods, Microwave and Infrared Heating, accelerate processing and provide effective ANF reduction while preserving high levels of nutrients (up to 90 %), and EMF Treatment offers targeted, moderate gains in zinc bioavailability and protein functionality (e.g., increasing gelation by 10–15 % in black beans). The highest overall efficiency is achieved through synergistic combined methods: for instance, Fermentation combined with Ultrasonic Treatment reduces phytate content by 60–85 % and simultaneously improves solubility by 20–30 % (chickpea), while Fermentation prior to Extrusion significantly mitigates the critical

Journal of Chemistry and Technologies, 2025, *33*(3), 1092-1117

issue of lysine loss in pea protein. These technologies promote the broader and more sustainable application of legumes in the production of functional foods, plant-based meat and dairy alternatives, and gluten-free products. For their successful industrial implementation and scaling, the findings underscore the necessity of dedicated research focused on optimizing processing parameters for combined methods while rigorously assessing energy consumption and economic feasibility as key factors for overcoming the current limitations to wide adoption.

A very important stage is the future prospects for research. Future development should focus on optimizing parameters for specific legume varieties (e.g., chickpeas, peas, soybeans) in order to precisely regulate the formation of bioactive peptides and beneficial aromatic compounds for specific end products [1; 12]. A critical path is the development of continuous, large-scale hybrid systems that seamlessly integrate highly efficient pretreatments such as ultrasonic treatment, infrared treatment to improve hydration and solubility [40; 54], with established industrial methods such as extrusion, thereby creating a cost-effective, high-throughput process that significantly reduces overall energy consumption [7]. In addition, advanced research should utilize unique protein modifications achieved through high pressure and ultrasonic processing to create specific functional properties (e.g., excellent foaming and emulsifying properties [3; 40]) for third-generation vegan products that require high stability and specific textural properties. Finally, to ensure broad market success, further research should integrate sustainability metrics and carefully address persistent sensory issues, particularly by controlling bitterness.

Overall, the comparative analysis highlights the priority potential of the technologies under investigation: fermentation and extrusion are the most promising and economically viable for large-scale implementation, ultrasonic treatment and high-pressure treatment provide targeted functional improvements, while electromagnetic field treatment remains an innovative but research-oriented approach. The uniqueness of each technology lies in its specific mechanism of action – from biological modification to non-thermal structural transformation – which determines its specific advantages. For practical application in Ukrainian production conditions, fermentation and extrusion are the most adaptable and resource-efficient methods, especially for locally grown legumes such as chickpeas, peas, and lentils.

References

[1]. Jimenez-Lopez, J. C., Singh, K. B., Clemente, A., Nelson, M. N., Ochatt, S., Smith, P. M. C. (2020). Editorial: Legumes for Global Food Security. Frontiers in Plant Science, 11. https://doi.org/10.3389/fpls.2020.00926

[2]. Gore, N. T., Shaikh, S. S., Sule, V. A., Umdale, S. D., Mundada, P. S., Gaikwad, N. B., Ahire, M. L. (2024). Understanding the nutritional profile of Vigna trilobata: A lesser-known, underexplored grain legume. *Food and Humanity, 3*, 100343. https://doi.org/10.1016/j.foohum.2024.100343

[3]. Neji, C., Semwal, J., Kamani, M. H., Máthé, E., Sipos, P. (2022). Legume protein extracts: The relevance of physical processing in the context of structural, techno-functional and nutritional aspects of food development. *Processes, 10*(12), 2586. https://doi.org/10.3390/pr1012586

[4]. Semba, R. D., Ramsing, R., Rahman, N., Kraemer, K., Bloem, M. W. (2021). Legumes as a sustainable source of protein in human diets. *Global Food Security, 28*, 100520. https://doi.org/10.1016/j.gfs.2021.100520

[5]. Vasconcelos, M. W., Grusak, M. A., Pinto, E., Gomes, A., Ferreira, H., Balázs, B., Centofanti, T., Ntatsi, G., Savvas, D., Karkanis, A., Williams, M., Vandenberg, A., Toma, L., Shrestha, S., Akaichi, F., Barrios, C. O., Gruber, S., James, E. K., Maluk, M., Karley, A., Iannetta, P. (2020). *The biology of legumes and their agronomic, economic, and social impact*. In Springer eBooks. https://doi.org/10.1007/978-981-15-4752-2_1

[6]. Carcea, M. (2020). Nutritional value of Grain-Based foods. *Foods, 9*(4), 504. https://doi.org/10.3390/foods9040504

[7]. Carbas, B., Machado, N., Pathania, S., Brites, C., Rosa, E. A., Barros, A. I. (2021). Potential of legumes: nutritional value, bioactive properties, innovative food products, and application of eco-friendly tools for their assessment. *Food Reviews International, 39*(1), 160–188. https://doi.org/10.1080/87559129.2021.1901292

[8]. Witten, S., Böhm, H., Aulrich, K. (2019). Effect of variety and environment on the contents of crude nutrients and amino acids in organically produced cereal and legume grains. *Organic Agriculture, 10*(2), 199–219. https://doi.org/10.1007/s13165-019-00261-7

[9]. Yiğit, A., Bielska, P., Cais-Sokolińska, D., Samur, G. (2023). Whey proteins as a functional food: Health effects, functional properties, and applications in food. *Journal of the American Nutrition Association, 42*(8), 758–768. https://doi.org/10.1080/27697061.2023.2169208

[10]. Martínez, J. M., Delso, C., Álvarez, I., Raso, J. (2020). Pulsed electric field-assisted extraction of valuable compounds from microorganisms. *Comprehensive Reviews in Food Science and Food Safety, 19*(2), 530–552. https://doi.org/10.1111/1541-4337.12512

[11]. Aziznia, S., Askari, G., Emamdjomeh, Z., Salami, M. (2023). Effect of ultrasonic assisted grafting on the structural and functional properties of mung bean protein isolate conjugated with maltodextrin through

maillard reaction. *International Journal of Biological Macromolecules, 254*, 127616. https://doi.org/10.1016/j.ijbiomac.2023.127616

[12]. Garrido-Galand, S., Asensio-Grau, A., Calvo-Lerma, J., Heredia, A., Andrés, A. (2021). The potential of fermentation on nutritional and technological improvement of cereal and legume flours: A review. *Food Research International, 145*, 110398. https://doi.org/10.1016/j.foodres.2021.110398

[13]. Tas, A. A., Shah, A. U. (2021). The replacement of cereals by legumes in extruded snack foods: Science, technology and challenges. Trends in Food Science & Technology, 116, 701–711. https://doi.org/10.1016/j.tifs.2021.08.016

[14]. Licandro, H., Ho, P. H., Nguyen, T. K. C., Petchkongkaew, A., Van Nguyen, H., Chu-Ky, S., Nguyen, T. V. A., Lorn, D., Waché, Y. (2019). How fermentation by lactic acid bacteria can address safety issues in legumes food products? *Food Control, 110*, 106957. https://doi.org/10.1016/j.foodcont.2019.106957

[15]. Pathiraje, D., Carlin, J., Der, T., Wanasundara, J. P. D., Shand, P. J. (2023). Generating Multi-Functional pulse ingredients for Processed meat Products—Scientific Evaluation of Infrared-Treated Lentils. *Foods, 12*(8), 1722. https://doi.org/10.3390/foods12081722

[16]. Ruiz-Zambrano, N. L., Pérez-Carrillo, E., Serna-Saldívar, S. O., Tejada-Ortigoza, V. (2023). Effect of thermal, nonthermal, and combined treatments on functional and nutritional properties of chickpeas. *Critical Reviews in Food Science and Nutrition, 64*(31), 11356–11374. https://doi.org/10.1080/10408398.2023.2237577

[17]. Joshi-Saha, A., Sethy, S. K., Misra, G., Dixit, G. P., Srivastava, A. K., Sarker, A. (2022). Biofortified legumes: Present scenario, possibilities and challenges. *Field Crops Research, 279*, 108467. https://doi.org/10.1016/j.fcr.2022.108467

[18]. De Oliveira Schmidt, H., De Oliveira, V. R. (2023). Overview of the Incorporation of Legumes into New Food Options: An Approach on Versatility, Nutritional, Technological, and Sensory Quality. *Foods, 12*(13), 2586. https://doi.org/10.3390/foods12132586

[19]. Chatur, P., Johnson, S., Coorey, R., Bhattarai, R. R., Bennett, S. J. (2022). The effect of high pressure processing on textural, bioactive and digestibility properties of cooked kimberley large Kabuli chickpeas. *Frontiers in Nutrition, 9*. https://doi.org/10.3389/fnut.2022.847877

[20]. Perera, D., Devkota, L., Garnier, G., Panozzo, J., Dhital, S. (2023). Hard-to-cook phenomenon in common legumes: Chemistry, mechanisms and utilisation. *Food Chemistry, 415,* 135743. https://doi.org/10.1016/j.foodchem.2023.135743

[21]. Wang, Y., Wang, Y., Li, K., Bai, Y., Li, B., Xu, W. (2020). Effect of high intensity ultrasound on physicochemical, interfacial and gel properties of chickpea protein isolate. *LWT, 129*, 109563. https://doi.org/10.1016/j.lwt.2020.109563

[22]. Mozafarpour, R., Koocheki, A., Nicolai, T. (2022). Modification of grass pea protein isolate (Lathyrus sativus L.) using high intensity ultrasound treatment: Structure and functional properties. *Food Research International, 158,* 111520. https://doi.org/10.1016/j.foodres.2022.111520

[23]. Teixeira, R. F., Filho, C. A. B., De Oliveira, D., Zielinski, A. A. F. (2023). Prospects on emerging eco-friendly and innovative technologies to add value to dry bean proteins. *Critical Reviews in Food Science and Nutrition*, *64*(28), 10256–10280. https://doi.org/10.1080/10408398.2023.2222179

[24]. Saffarionpour, S. (2023). Off-Flavors in pulses and grain Legumes and Processing Approaches for Controlling Flavor-Plant Protein interaction: Application Prospects in Plant-Based Alternative Foods. *Food and Bioprocess Technology, 17*(5), 1141–1182. https://doi.org/10.1007/s11947-023-03148-4

[25]. Senanayake, D., Torley, P. J., Chandrapala, J., Terefe, N. S. (2023). Microbial fermentation for improving the sensory, nutritional and functional attributes of legumes. *Fermentation, 9*(7), 635. https://doi.org/10.3390/fermentation9070635

[26]. Ohanenye, I. C., Ekezie, F.-G. C., Sarteshnizi, R. A., Boachie, R. T., Emenike, C. U., Sun, X., Nwachukwu, I. D., Udenigwe, C. C. (2022). Legume seed protein digestibility as influenced by traditional and emerging physical processing technologies. *Foods, 11*(15), 2299. https://doi.org/10.3390/foods11152299

[27]. Fernando, S. (2021). Pulse protein ingredient modification. *Journal of the Science of Food and Agriculture, 102*(3), 892–897. https://doi.org/10.1002/jsfa.11548

[28]. Tidåker, P., Potter, H. K., Carlsson, G., Röös, E. (2021). Towards sustainable consumption of legumes: How origin, processing and transport affect the environmental impact of pulses. *Sustainable Production and Consumption, 27*, 496–508. https://doi.org/10.1016/j.spc.2021.01.017

[29]. Wei, Y., Ning, D., Sun, L., Gu, Y., Zhuang, Y., Ding, Y., Fan, X. (2025). Breaking barriers: Elevating legume protein functionality in food products through non-thermal technologies. *Food Chemistry X, 25*, 102169. https://doi.org/10.1016/j.fochx.2025.102169

[30]. Affrifah, N. S., Uebersax, M. A., Amin, S. (2023). Nutritional significance, value-added applications, and consumer perceptions of food legumes: A review. *Legume Science, 5*(4). https://doi.org/10.1002/leg3.192

[31]. Bautista-Expósito, S., Vandenberg, A., Peñas, E., Frias, J., Martínez-Villaluenga, C. (2021). Lentil and fava bean with contrasting germination kinetics: a focus on digestion of proteins and bioactivity of resistant peptides. *Frontiers in Plant Science, 12.* https://doi.org/10.3389/fpls.2021.754287

[32]. Oh, S.-M., Song, S.-B., Lee, J.-S., Oh, Y.-G., Choi, Y.-C., Lee, J.-H., Kwak, J. (2022). Effect of Microwave Treatment on Adzuki Beans (Vigna angularis L.) under Dry State—Analyzing Microstructure, Water Absorption, and Antioxidant Properties. *Foods, 11*(11), 1653. https://doi.org/10.3390/foods11111653

[33]. Lai, X.-J., Chen, J.-Q., Nie, J., Guo, P.-F., Manzoor, M. F., Huang, Y.-Y., Li, J., Lin, S.-Y., Zeng, X.-A., Wang, R. (2024). Enhancement of extraction efficiency and functional properties of chickpea protein isolate using pulsed electric field combined with ultrasound treatment. *Ultrasonics Sonochemistry, 111*, 107089. https://doi.org/10.1016/j.ultsonch.2024.107089

[34]. Saran, V., Pavithra, R., Koli, V., Dattatrya, P. A., Nikashini, T., Ashika, R., Gowda, N. A. N., Sunil, C. K. (2024). Ultrasound modification of techno-functional, structural, and physico-chemical properties of legume proteins: A Review. *Food Bioscience, 60,* 104456. https://doi.org/10.1016/j.fbio.2024.104456

[35]. Bandyopadhyay, M., Guha, S., Naldrett, M. J., Alvarez, S., Majumder, K. (2021). Evaluating the effect of high-

pressure processing in contrast to boiling on the antioxidant activity from alcalase hydrolysate of Great Northern Beans (Phaseolus vulgaris). *Journal of Food Biochemistry, 45*(12). https://doi.org/10.1111/jfbc.14004

[36]. Sridhar, K., Bouhallab, S., Croguennec, T., Renard, D., Lechevalier, V. (2022). Application of high-pressure and ultrasound technologies for legume proteins as wall material in microencapsulation: New insights and advances. *Trends in Food Science & Technology, 127*, 49–62. https://doi.org/10.1016/j.tifs.2022.07.006

[37]. Lin, T., Fernández-Fraguas, C. (2020). Effect of thermal and high-pressure processing on the thermo-rheological and functional properties of common bean (Phaseolus vulgaris L.) flours. *LWT, 127*, 109325. https://doi.org/10.1016/j.lwt.2020.109325

[38]. Bhargava, N., Mor, R. S., Kumar, K., Sharanagat, V. S. (2020). Advances in application of ultrasound in food processing: A review. Ultrasonics Sonochemistry, 70, 105293. https://doi.org/10.1016/j.ultsonch.2020.105293

[39]. Badjona, A., Bradshaw, R., Millman, C., Howarth, M., Dubey, B. (2024). Structural, thermal, and physicochemical properties of ultrasound-assisted extraction of faba bean protein isolate (FPI). *Journal of Food Engineering, 377,* 112082. https://doi.org/10.1016/j.jfoodeng.2024.112082

[40]. Kang, S., Zhang, J., Guo, X., Lei, Y., Yang, M. (2022). Effects of ultrasonic treatment on the structure, functional properties of chickpea protein isolate and its digestibility in vitro. Foods, 11 (6), 880. https://doi.org/10.3390/foods11060880

[41]. Das, D., Panesar, P. S., Saini, C. S. (2023). Ultrasonic extraction of soy protein isolate: Characterization and comparison with microwave and enzymatic extraction methods. *Journal of Food Science, 88*(7), 2758–2779. https://doi.org/10.1111/1750-3841.16654

[42]. Locatelli, M., Coïsson, J. D., Travaglia, F., Cereti, E., Garino, C., D'Andrea, M., Martelli, A., Arlorio, M. (2011). Chemotype and genotype chemometrical evaluation applied to authentication and traceability of "Tonda Gentile Trilobata" hazelnuts from Piedmont (Italy). *Food Chemistry, 129*(4), 1865–1873. https://doi.org/10.1016/j.foodchem.2011.05.134

[43]. Siddiq, M., Uebersax, M. A. (2021). *Dry Beans and Pulses*, Wiley. https://doi.org/10.1002/9781119776802

[44]. Ashraf, J., Liu, L., Awais, M., Xiao, T., Wang, L., Zhou, X., Tong, L.-T., Zhou, S. (2020). Effect of thermosonication pre-treatment on mung bean (Vigna radiata) and white kidney bean (Phaseolus vulgaris) proteins: Enzymatic hydrolysis, cholesterol lowering activity and structural characterization. Ultrasonics Sonochemistry, 66, 105121. https://doi.org/10.1016/j.ultsonch.2020.105121

[45]. Yeasmin, F., Prasad, P., Sahu, J. K. (2024). Effect of ultrasound on physicochemical, functional and antioxidant properties of red kidney bean (Phaseolus vulgaris L.) proteins extract. Food Bioscience, 57, 103599. https://doi.org/10.1016/j.fbio.2024.103599

[46]. Bender, D., Yamsaengsung, R., Waziiroh, E., Schoenlechner, R., Jaeger, H. (2024). Effect of ultrasound-assisted soaking on the hydration kinetics and physicochemical properties of chickpeas. *International Journal of Food Science & Technology, 59* (4), 2221–2235. https://doi.org/10.1111/ijfs.16916

[47]. Lukacs, M., Somogyi, T., Mukite, B. M., Vitális, F., Kovacs, Z., Rédey, Á., Stefaniga, T., Zsom, T., Kiskó, G., Zsom-Muha, V. (2025). Investigation of the Ultrasonic Treatment-Assisted soaking process of different red kidney beans and compositional analysis of the soaking water by NIR spectroscopy. *Sensors, 25*(2), 313. https://doi.org/10.3390/s25020313

[48]. Loushigam, G., Shanmugam, A. (2023). Modifications to functional and biological properties of proteins of cowpea pulse crop by ultrasound-assisted extraction. *Ultrasonics Sonochemistry, 97,* 106448. https://doi.org/10.1016/j.ultsonch.2023.106448

[49]. Aghababaei, F., McClements, D. J., Hadidi, M. (2024). Ultrasound processing for enhanced digestibility of plant proteins. Food Hydrocolloids, 155, 110188. https://doi.org/10.1016/j.foodhyd.2024.110188

[50]. John, R., Bartwal, A., Jeyaseelan, C., Sharma, P., Ananthan, R., Singh, A. K., Singh, M., Gayacharan, N., Rana, J. C., Bhardwaj, R. (2023). Rice bean-adzuki bean multitrait near infrared reflectance spectroscopy prediction model: a rapid mining tool for trait-specific germplasm. *Frontiers in Nutrition, 10.* https://doi.org/10.3389/fnut.2023.1224955

[51]. Lao, Y., Ye, Q., Wang, Y., Selomulya, C. (2024). Modulating digestibility and mitigating beany flavor of pea protein. *Food Reviews International, 40*(9), 3129–3158. https://doi.org/10.1080/87559129.2024.2346329

[52]. Najib, T., Heydari, M. M., Meda, V. (2022). Combination of germination and innovative microwave-assisted infrared drying of lentils: effect of physicochemical properties of different varieties on water uptake, germination, and drying kinetics. *Applied Food Research, 2*(1), 100040. https://doi.org/10.1016/j.afres.2021.100040

[53]. Pasqualone, A., Costantini, M., Coldea, T. E., Summo, C. (2020). Use of legumes in extrusion cooking: a review. *Foods, 9*(7), 958. https://doi.org/10.3390/foods9070958

[54]. Rico, D., Cano, A. B., Martín-Diana, A. B. (2021). Pulse-Cereal blend extrusion for improving the antioxidant properties of a Gluten-Free flour. *Molecules, 26*(18), 5578. https://doi.org/10.3390/molecules26185578

[55]. Zang, Y., Wang, S., Gao, Y., Sun, C., Zhao, Y., Cao, Y., Lu, W., Zhang, Y., Fang, Y. (2024). High moisture extrusion of pulse proteins: texture, structure, and in vitro digestion characteristics of extrudates. *Food Hydrocolloids*, 110676. https://doi.org/10.1016/j.foodhyd.2024.110676

[56]. Ciudad-Mulero, M., Vega, E. N., García-Herrera, P., Pedrosa, M. M., Arribas, C., De J Berrios, J., Cámara, M., Fernández-Ruiz, V., Morales, P. (2022). Extrusion cooking effect on carbohydrate fraction in novel Gluten-Free flours based on chickpea and rice. *Molecules, 27* (3), 1143. https://doi.org/10.3390/molecules27031143

[57]. Ek, P., Baner, J. M., Ganjyal, G. M. (2020). *Extrusion processing of cereal grains, tubers, and seeds*. In Elsevier eBooks. https://doi.org/10.1016/b978-0-12-815360-4.00008-0

[58]. Pedrosa, M. M., Guillamón, E., Arribas, C. (2021). Autoclaved and extruded legumes as a source of bioactive phytochemicals: a review. *Foods, 10*(2), 379. https://doi.org/10.3390/foods10020379

[59]. Cotacallapa-Sucapuca, M., Vega, E. N., Maieves, H. A., De J Berrios, J., Morales, P., Fernández-Ruiz, V., Cámara, M. (2021). Extrusion process as an alternative to improve pulses products consumption. a review. *Foods, 10*(5), 1096. https://doi.org/10.3390/foods10051096

[60]. Kristiawan, M., Della Valle, G., Berzin, F. (2022). Extrusion simulation for the design of cereal and legume foods. *Foods, 11*(12), 1780. https://doi.org/10.3390/foods11121780
[61]. Andersone-Trezina, E., Kince, T. (2022). Use of peas (Pisum Sativum L.) and beans (Phaseolus Vulgaris L.) In high-moisture food extrusion: a review. *Research for Rural Development/Research for Rural Development* (Online), 37, 93–99. https://doi.org/10.22616/rrd.28.2022.014
[62]. Jain, R., Goomer, S. (2023). Understanding extrusion technology for cereal–pulse blends: A review. *Cogent Food & Agriculture, 9*(1). https://doi.org/10.1080/23311932.2023.2253714
[63]. Cargo-Froom, C. L., Newkirk, R. W., Marinangeli, C. P. F., Shoveller, A. K., Ai, Y., Columbus, D. A. (2022). The effects of extrusion on nutrient content of Canadian pulses with a focus on protein and amino acids. *Canadian Journal of Animal Science, 103*(1), 44–58. https://doi.org/10.1139/cjas-2022-0088
[64]. Duque-Estrada, P., Hardiman, K., Dam, A. B., Dodge, N., Aaslyng, M. D., Petersen, I. L. (2023). Protein blends and extrusion processing to improve the nutritional quality of plant proteins. *Food & Function, 14*(16), 7361–7374. https://doi.org/10.1039/d2fo03912e
[65]. Faliarizao, N., De J Berrios, J., Dolan, K. D. (2024). Value-Added processing of food legumes using extrusion Technology: A review. *Legume Science, 6*(2). https://doi.org/10.1002/leg3.231
[66]. Siitonen, A., Nieminen, F., Kallio, V., Tuccillo, F., Kantanen, K., Ramos-Diaz, J. M., Jouppila, K., Piironen, V., Kariluoto, S., Edelmann, M. (2024). B vitamins in legume ingredients and their retention in high moisture extrusion. *Foods, 13*(5), 637. https://doi.org/10.3390/foods13050637
[67]. Bakhsh, A., Son, Y., Kim, B., Chin, J., Park, S. (2023). Optimizing extrusion processes: Development of extrudates utilizing ISP and wheat gluten, incorporating diverse concentrations of rice or legume varieties. Journal of Agriculture and Food Research, 15, 100915. https://doi.org/10.1016/j.jafr.2023.100915
[68]. Gu, J., Bk, A., Wu, H., Lu, P., Nawaz, M. A., Barrow, C. J., Dunshea, F. R., Suleria, H. A. R. (2022). Impact of processing and storage on protein digestibility and bioavailability of legumes. *Food Reviews International, 39*(7), 4697–4724. https://doi.org/10.1080/87559129.2022.2039690
[69]. Altan, A., Yağci, S. (2023). Physicochemical characteristics and structural changes of fermented faba bean extrudates prepared by twin-screw extrusion. *Food Chemistry, 411*, 135502. https://doi.org/10.1016/j.foodchem.2023.135502
[70]. Guo, L., Wang, X., Ren, Y., Zhang, X., Li, Q., Zhang, C., Qian, J.-Y. (2023). Outcomes of structure, function and flavor of pea protein isolate treated by AC, DC and pulsed electric fields. *Food Research International, 176*, 113817. https://doi.org/10.1016/j.foodres.2023.113817
[71]. Mulla, M. Z., Subramanian, P., Dar, B. N. (2022). Functionalization of legume proteins using high pressure processing: Effect on technofunctional properties and digestibility of legume proteins. *LWT, 158*, 113106. https://doi.org/10.1016/j.lwt.2022.113106
[72]. Peyrano, F., De Lamballerie, M., Avanza, M. V., Speroni, F. (2020). Gelation of cowpea proteins induced by high hydrostatic pressure. *Food Hydrocolloids, 111*, 106191. https://doi.org/10.1016/j.foodhyd.2020.106191
[73]. Yanni, A. E., Iakovidi, S., Vasilikopoulou, E., Karathanos, V. T. (2023). Legumes: a vehicle for Transition to Sustainability. *Nutrients, 16*(1), 98. https://doi.org/10.3390/nu16010098
[74]. Sá, A. G. A., Da Silva, D. C., Pacheco, M. T. B., Moreno, Y. M. F., Carciofi, B. A. M. (2021). Oilseed by-products as plant-based protein sources: Amino acid profile and digestibility. *Future Foods, 3*, 100023. https://doi.org/10.1016/j.fufo.2021.100023
[75]. Kamani, M. H., Neji, C., Fitzsimons, S. M., Fenelon, M. A., Murphy, E. G. (2023). Unlocking the nutritional and functional potential of legume waste to produce protein ingredients. *Critical Reviews in Food Science and Nutrition, 64*(21), 7311–7329. https://doi.org/10.1080/10408398.2023.2184322
[76]. Hall, A. E., Moraru, C. I. (2021). Structure and function of pea, lentil and faba bean proteins treated by high pressure processing and heat treatment. LWT, 152, 112349. https://doi.org/10.1016/j.lwt.2021.112349
[77]. Wiesinger, J. A., Marsolais, F., Glahn, R. P. (2021). *Health Implications and Nutrient Bioavailability of Bioactive Compounds in Dry Beans and Other Pulses*. In Dry Beans and Pulses. https://doi.org/10.1002/9781119776802.ch20
[78]. Gharibzahedi, S. M. T., Smith, B. (2020). Effects of high hydrostatic pressure on the quality and functionality of protein isolates, concentrates, and hydrolysates derived from pulse legumes: A review. Trends in Food Science & Technology, 107, 466–479. https://doi.org/10.1016/j.tifs.2020.11.016
[79]. Sosa, E. F., Thompson, C., Chaves, M. G., Acevedo, B. A., Avanza, M. V. (2019). Legume seeds treated by high hydrostatic pressure: Effect on functional properties of flours. *Food and Bioprocess Technology, 13*(2), 323–340. https://doi.org/10.1007/s11947-019-02386-9
[80]. Kamboj, S., Gupta, N., Bandral, J. D., Gandotra, G., Anjum, N. (2020). Food safety and hygiene: A review. *International Journal of Chemical Studies, 8*(2), 358–368. https://doi.org/10.22271/chemi.2020.v8.i2f.8794
[81]. Erem, E., Icyer, N. C., Tatlisu, N. B., Kilicli, M., Kaderoglu, G. H., Toker, Ö. S. (2021). A new trend among plant-based food ingredients in food processing technology: Aquafaba. *Critical Reviews in Food Science and Nutrition, 63*(20), 4467–4484. https://doi.org/10.1080/10408398.2021.2002259
[82]. Nguyen, T. T. B., Li, D. (2021). A systematic literature review of food safety management system implementation in global supply chains. *British Food Journal, 124*(10), 3014–3031. https://doi.org/10.1108/bfj-05-2021-0476
[83]. Hasani, M., Camacho-Martinez, S. V., Warriner, K. (2024). Food safety management systems. In Elsevier eBooks: pp 241–254. https://doi.org/10.1016/b978-0-443-15690-8.00021-7
[84]. Carlini, B., Lucini, C., Velázquez, J. (2024). The Role of Legumes in the Sustainable Mediterranean Diet: Analysis of the Consumption of Legumes in the Mediterranean Population over the Last Ten Years a PRISMA Statement Methodology. *Sustainability, 16*(7), 3081. https://doi.org/10.3390/su16073081
[85]. Sharma, A. (2020). A review on traditional technology and safety challenges with regard to antinutrients in legume foods. *Journal of Food Science and Technology, 58*(8), 2863–2883. https://doi.org/10.1007/s13197-020-04883-8

[86]. Knorr, D. (2023). Food processing: Legacy, significance and challenges. Trends in Food Science & Technology, 143, 104270. https://doi.org/10.1016/j.tifs.2023.104270
[87]. Lee, J. C., Neonaki, M., Alexopoulos, A., Varzakas, T. (2023). Case Studies of Small-Medium Food Enterprises around the World: Major Constraints and Benefits from the Implementation of Food Safety Management Systems. Foods, 12 (17), 3218. https://doi.org/10.3390/foods12173218
[88]. Ding, Y., Ban, Q., Wu, Y., Sun, Y., Zhou, Z., Wang, Q., Cheng, J., Xiao, H. (2021). Effect of high hydrostatic pressure on the edible quality, health and safety attributes of plant-based foods represented by cereals and legumes: a review. Critical Reviews in Food Science and Nutrition, 63 (20), 4636–4654. https://doi.org/10.1080/10408398.2021.2005531
[89]. Sun, X., Ohanenye, I. C., Ahmed, T., Udenigwe, C. C. (2020). Microwave treatment increased protein digestibility of pigeon pea (Cajanus cajan) flour: Elucidation of underlying mechanisms. Food Chemistry, 329, 127196. https://doi.org/10.1016/j.foodchem.2020.127196
[90]. Nardi, V. A. M., Auler, D. P., Teixeira, R. (2020). Food safety in global supply chains: A literature review. Journal of Food Science, 85 (4), 883–891. https://doi.org/10.1111/1750-3841.14999
[91]. Mishra, S., Singh, R., Upadhyay, A., Mishra, S., Shukla, S. (2023). Emerging trends in processing for cereal and legume-based beverages: A review. Future Foods, 8, 100257. https://doi.org/10.1016/j.fufo.2023.100257
[92]. Shah, H., Ahmed, L., Barry-Ryan, C. (2024). Ensuring compliance: A review of EU regulations and standards for incorporating legume and legume by-product proteins in food formulations. *Heliyon, 10*(21), e39821. https://doi.org/10.1016/j.heliyon.2024.e39821
[93]. Bessada, S. M. F., Barreira, J. C. M., Oliveira, M. B. P. P. (2019). Pulses and food security: Dietary protein, digestibility, bioactive and functional properties. *Trends in Food Science & Technology, 93*, 53–68. https://doi.org/10.1016/j.tifs.2019.08.022
[94]. Semwal, J., Meera. (2020). Infrared radiation: Impact on physicochemical and functional characteristics of grain starch. *Starch - Stärke, 73*(3–4). https://doi.org/10.1002/star.202000112
[95]. Rana, R. L., Tricase, C., De Cesare, L. (2021). Blockchain technology for a sustainable agri-food supply chain. British Food Journal, 123 (11), 3471–3485. https://doi.org/10.1108/bfj-09-2020-0832
[96]. Malik, S., Krishnaswamy, K., Mustapha, A. (2021). Hazard Analysis and Risk-Based Preventive Controls (HARPC): Current food safety and quality standards for complementary foods. *Foods, 10*(9), 2199. https://doi.org/10.3390/foods10092199
[97]. Radoiu, M., Calvo-Carrascal, M. A., Dodds, C., Binner, E.R. (2021). Flash microwave denaturation of POD and LOX enzymes in whole yellow peas. *Chemical Engineering and Processing - Process Intensification, 169*, 108601. https://doi.org/10.1016/j.cep.2021.108601
[98]. Alandia, G., Pulvento, C., Sellami, M. H., Hoidal, N., Anemone, T., Nigussie, E., Agüero, J. J., Lavini, A., Jacobsen, S. -e. (2020). *Grain legumes may enhance High-Quality food production in Europe*. In Environment & policy. https://doi.org/10.1007/978-3-319-90472-6_2
[99]. Mahalaxmi, S., Himashree, P., Malini, B., Sunil, C. K. (2022). Effect of microwave treatment on the structural and functional properties of proteins in lentil flour. Food Chemistry Advances, 1, 100147. https://doi.org/10.1016/j.focha.2022.100147
[100]. Duan, H.-X., Luo, C.-L., Wang, X., Cheng, Y.-S., Abrar, M., Batool, A. (2024). Responses of legumes to rhizobia and arbuscular mycorrhizal fungi under abiotic stresses: A Global Meta-Analysis. Agronomy, 14 (11), 2597. https://doi.org/10.3390/agronomy14112597
[101]. Abass, N. T., Eruaga, N. M. A., Itua, N. E. O., Bature, N. J. T. (2024). ADVANCING FOOD SAFETY THROUGH IOT: REAL-TIME MONITORING AND CONTROL SYSTEMS. International Medical Science Research Journal, 4 (3), 276–283. https://doi.org/10.51594/imsrj.v4i3.919
[102]. Bosona, T., Gebresenbet, G. (2023). The role of blockchain technology in promoting traceability systems in Agri-Food production and supply chains. Sensors, 23 (11), 5342. https://doi.org/10.3390/s23115342
[103]. Li, M., Wang, B., Lv, W., Zhao, D. (2022). Effect of ultrasound pretreatment on the drying kinetics and characteristics of pregelatinized kidney beans based on microwave-assisted drying. Food Chemistry, 397, 133806. https://doi.org/10.1016/j.foodchem.2022.133806
[104]. Antonenko, A., Tolok, G., Brovenko, T., Biriukova, O., Ratushenko, A., Gorkun, A. (2024). AUDIT AND QUALITY CONTROL OF FOOD PRODUCTS IN EU COUNTRIES AND THE WORLD. Measuring and Computing Devices in Technological Processes, No. 4, 18–22. https://doi.org/10.31891/2219-9365-2024-80-2
[105]. Xu, Y., Li, X., Zeng, X., Cao, J., Jiang, W. (2020). Application of blockchain technology in food safety control : current trends and future prospects. *Critical Reviews in Food Science and Nutrition, 62*(10), 2800–2819. https://doi.org/10.1080/10408398.2020.1858752
[106]. Segura, M., Maroto, C., Segura, B., Casas-Rosal, J. C. (2020). Improving food supply chain management by a sustainable approach to supplier evaluation. *Mathematics, 8*(11), 1952. https://doi.org/10.3390/math8111952
[107]. Heydari, M. M., Kauldhar, B. S., Meda, V. (2020). Kinetics of a thin-layer microwave-assisted infrared drying of lentil seeds. *Legume Science, 2*(2). https://doi.org/10.1002/leg3.31
[108]. Badjona, A., Bradshaw, R., Millman, C., Howarth, M., Dubey, B. (2023). FABA Bean Processing: Thermal and Non-Thermal Processing on chemical, antinutritional factors, and pharmacological properties. *Molecules, 28* (14), 5431. https://doi.org/10.3390/molecules28145431
[109]. Zuluaga, A. M., Mena-García, A., Monzón, A. C. S., Rada-Mendoza, M., Chito, D. M., Ruiz-Matute, A. I., Sanz, M. L. (2020). Microwave assisted extraction of inositols for the valorization of legume by-products. *LWT, 133*, 109971. https://doi.org/10.1016/j.lwt.2020.109971
[110]. Safitri, R. A., Van Asselt, E. D., Müller-Maatsch, J., Vogelgsang, S., Dapcevic-Hadnadev, T., De Nijs, M. (2024). Generic food safety assessment: A framework to evaluate food safety hazards emerging from change(s) in the primary production system – A case study involving intercropping. *Journal of Food Protection*, 100371. https://doi.org/10.1016/j.jfp.2024.100371
[111]. Bomba, M. Ya., Susol, N. Ya. (2020). Main requirements for food safety management systems under international standards: BRC, IFS, FSSC 22000, ISO 22000, Global GAP, SQF. *Scientific Messenger of LNU*

of Veterinary Medicine and Biotechnologies, 22(93), 18–25. https://doi.org/10.32718/nvlvet-f9304

[112]. Pierre, J. F. (2024). *Legumes: cornerstones of global food security and sustainable agriculture*. In IntechOpen eBooks. https://doi.org/10.5772/intechopen.1006180

[113]. Amoah, I., Ascione, A., Muthanna, F., Feraco, A., Camajani, E., Gorini, S., Armani, A., Caprio, M., Lombardo, M. (2023). Sustainable Strategies for Increasing legume Consumption: Culinary and educational approaches. *Foods, 12*(11), 2265. https://doi.org/10.3390/foods12112265

[114]. Lau, H., Nakandala, D., Shum, P. K. A (2018). business process decision model for fresh-food supplier evaluation. *Business Process Management Journal, 24*(3), 716–744. https://doi.org/10.1108/bpmj-01-2016-0015

[115]. Wu, X.-F., Zhang, M., Bhandari, B. (2019). A novel infrared freeze drying (IRFD) technology to lower the energy consumption and keep the quality of Cordyceps militaris. *Innovative Food Science & Emerging Technologies, 54*, 34–42. https://doi.org/10.1016/j.ifset.2019.03.003

[116]. Heydari, M. M., Najib, T., Meda, V. (2022). Investigating starch and protein structure alterations of the processed lentil by microwave-assisted infrared thermal treatment and their correlation with the modified properties. *Food Chemistry Advances, 1*, 100091. https://doi.org/10.1016/j.focha.2022.100091

[117]. Guldiken, B., Konieczny, D., Franczyk, A., Satiro, V., Pickard, M., Wang, N., House, J., Nickerson, M. T. (2022). Impacts of infrared heating and tempering on the chemical composition, morphological, functional properties of navy bean and chickpea flours. *European Food Research and Technology, 248*(3), 767–781. https://doi.org/10.1007/s00217-021-03918-4

[118]. Rahman, M. M., Refat, B., Zhang, H., Zhang, W., Yu, P. (2018). Detect molecular spectral features of newly developed Vicia faba varieties and protein metabolic characteristics in ruminant system using advanced synchrotron radiation based infrared microspectroscopy: A preliminary study. *Spectrochimica Acta Part a Molecular and Biomolecular Spectroscopy, 206*, 413–420. https://doi.org/10.1016/j.saa.2018.08.022

[119]. Iqbal, A., Hosseini, A. F., Rizvi, S. S. H. (2025). Supercritical fluid extrusion of pea flour and pea protein concentrate: Effects on off-flavor removal and sensory improvement. *Journal of Food Science, 90*(1). https://doi.org/10.1111/1750-3841.70004

[120]. Acquah, C., Ohemeng-Boahen, G., Power, K. A., Tosh, S. M. (2021). The effect of processing on bioactive compounds and nutritional qualities of pulses in meeting the Sustainable Development Goal 2. *Frontiers in Sustainable Food Systems, 5*. https://doi.org/10.3389/fsufs.2021.681662

[121]. López-Calabozo, R., Liberal, Â., Fernandes, Â., Revilla, I., Ferreira, I. C. F. R., Barros, L., Vivar-Quintana, A. M. (2024). Determination of carbohydrate composition in lentils using Near-Infrared Spectroscopy. *Sensors, 24*(13), 4232. https://doi.org/10.3390/s24134232

[122]. Manyatsi, T. S., Al-Hilphy, A. R., Majzoobi, M., Farahnaky, A., Gavahian, M. (2022). Effects of infrared heating as an emerging thermal technology on physicochemical properties of foods. *Critical Reviews in Food Science and Nutrition, 63*(24), 6840–6859. https://doi.org/10.1080/10408398.2022.2043822

[123]. Deepika, S., Sutar, P. P. (2023). Spectral selective infrared heating of food components based on optical characteristics and penetration depth: a critical review. *Critical Reviews in Food Science and Nutrition*, 1–23. https://doi.org/10.1080/10408398.2023.2227899

[124]. Liu, S., Ren, Y., Yin, H., Nickerson, M., Pickard, M., Ai, Y. (2022). Improvement of the nutritional quality of lentil flours by infrared heating of seeds varying in size. *Food Chemistry, 396*, 133649. https://doi.org/10.1016/j.foodchem.2022.133649

[125]. Sakare, P., Prasad, N., Thombare, N., Singh, R., Sharma, S. C. (2020). Infrared drying of food materials: recent advances. *Food Engineering Reviews, 12*(3), 381–398. https://doi.org/10.1007/s12393-020-09237-w

[126]. Mizutani, Y., Shibata, M., Yamada, S., Nambu, Y., Hirotsuka, M., Matsumura, Y. (2018). Effects of heat treatment under low moisture conditions on the protein and oil in soybean seeds. *Food Chemistry, 275*, 577–584. https://doi.org/10.1016/j.foodchem.2018.09.139

[127]. Rivera, J., Siliveru, K., Li, Y. (2022). A comprehensive review on pulse protein fractionation and extraction: processes, functionality, and food applications. *Critical Reviews in Food Science and Nutrition, 64*(13), 4179–4201. https://doi.org/10.1080/10408398.2022.2139223

[128]. Galvão, A. M. M. T., Rasera, M. L., De Figueiredo Furtado, G., Karatay, G. G. B., Tavares, G. M., Hubinger, M. D. (2024). Lentil protein isolate (Lens culinaris) subjected to ultrasound treatment combined or not with heat-treatment: structural characterization and ability to stabilize high internal phase emulsions. *Food Research International, 183*, 114212. https://doi.org/10.1016/j.foodres.2024.114212

[129]. Daba, S. D., Honigs, D., McGee, R. J., Kiszonas, A. M. (2022). Prediction of Protein Concentration in Pea (Pisum sativum L.) Using Near-Infrared Spectroscopy (NIRS) *Systems. Foods, 11*(22), 3701. https://doi.org/10.3390/foods11223701

[130]. Ferreira, H., Pinto, E., Vasconcelos, M. W. (2021). Legumes as a cornerstone of the transition toward more sustainable Agri-Food systems and diets in Europe. *Frontiers in Sustainable Food Systems, 5*. https://doi.org/10.3389/fsufs.2021.694121

[131]. Ahmed, J. (2021). *Emerging technologies for pulse processing*. In Elsevier eBooks. https://doi.org/10.1016/b978-0-12-818184-3.00011-8

[132]. Das, P. C., Baik, O., Tabil, L. G., Rajagopalan, N. (2025). Impact of radiofrequency and microwave heating on the nutritional and antinutritional properties of pulses: a review. *Legume Science, 7*(1). https://doi.org/10.1002/leg3.70025

[133]. Johnston, C., Leong, S. Y., Teape, C., Liesaputra, V., Oey, I. (2024). Low-intensity pulsed electric field processing prior to germination improves in vitro digestibility of faba bean (Vicia faba L.) flour and its derived products: A case study on legume-enriched wheat bread. *Food Chemistry, 449*, 139321. https://doi.org/10.1016/j.foodchem.2024.139321

[134]. Cao, H., Wang, X., Liu, J., Sun, Z., Yu, Z., Battino, M., El-Seedi, H., Guan, X. (2023). Mechanistic insights into the changes of enzyme activity in food processing under microwave irradiation. *Comprehensive Reviews in Food Science and Food Safety, 22*(3), 2465–2487. https://doi.org/10.1111/1541-4337.13154

[135]. Gharibzahedi, S. M. T., Smith, B., Altintas, Z. (2022). Bioactive and health-promoting properties of

enzymatic hydrolysates of legume proteins: a review. *Critical Reviews in Food Science and Nutrition, 64*(9), 2548–2578. https://doi.org/10.1080/10408398.2022.2124399

[136]. Najib, T., Heydari, M. M., Tu, K., Meda, V. (2023). Modification in starch structure of soaked and germinated lentil seeds under various thermal processing methods, including conventional, microwave, and microwave-assisted techniques. *Food Chemistry Advances, 2,* 100267. https://doi.org/10.1016/j.focha.2023.100267

[137]. Zhou, J., Li, M., Bai, Q., De Souza, T. S. P., Barrow, C., Dunshea, F., Suleria, H. a. R. (2023). Effects of different processing methods on pulses Phytochemicals: An Overview. *Food Reviews International, 40*(4), 1138–1195. https://doi.org/10.1080/87559129.2023.2212041

[138]. İşçimen, E. M., Hayta, M. (2021). Microwave-assisted aqueous two-phase system based extraction of phenolics from pulses: Antioxidant properties, characterization and encapsulation. *Industrial Crops and Products, 173,* 114144. https://doi.org/10.1016/j.indcrop.2021.114144

[139]. Bou, R., Navarro-Vozmediano, P., Domínguez, R., López-Gómez, M., Pinent, M., Ribas-Agustí, A., Benedito, J. J., Lorenzo, J. M., Terra, X., García-Pérez, J. V., Pateiro, M., Herrera-Cervera, J. A., Jorba-Martín, R. (2022). Application of emerging technologies to obtain legume protein isolates with improved techno-functional properties and health effects. *Comprehensive Reviews in Food Science and Food Safety, 21*(3), 2200–2232. https://doi.org/10.1111/1541-4337.12936

[140]. Laing, E., Stone, A. K., Shi, D., Pickard, M., House, J. D., Wang, N., Nickerson, M. T. (2023). Effect of infrared heating on the nutritional properties of yellow pea and green lentil flours. *Cereal Chemistry, 100*(3), 614–627. https://doi.org/10.1002/cche.10653

[141]. Sá, A. G. A., Laurindo, J. B., Moreno, Y. M. F., Carciofi, B. A. M. (2022). Influence of emerging technologies on the utilization of plant proteins. Frontiers in Nutrition, 9. https://doi.org/10.3389/fnut.2022.809058

[142]. Mahmood, N., Muhoza, B., Kothakot, A., Munir, Z., Huang, Y., Zhang, Y., Pandiselvam, R., Iqbal, S., Zhang, S., Li, Y. (2023). Application of emerging thermal and nonthermal technologies for improving textural properties of food grains: A critical review. *Comprehensive Reviews in Food Science and Food Safety, 23*(1). https://doi.org/10.1111/1541-4337.13286

[143]. Lara, L. M., Wilson, S. A., Chen, P., Atungulu, G. G. (2019). The effects of infrared treatment on physicochemical characteristics of vegetable soybean. *Heliyon, 5*(1), e01148. https://doi.org/10.1016/j.heliyon.2019.e01148