Sustainable
Food Technology

ROYAL SOCIETY OF CHEMISTRY

REVIEW

View Article Online
View Journal | View Issue

Cite this: *Sustainable Food Technol.*, 2026, 4, 261

Faba bean: sustainable potential in Brazilian agriculture and biorefineries as a rich source of proteins, starch, and fibers, along with its antinutrient challenges

Luiz Eliel Pinheiro da Silva,[ab] Thaís Caroline Buttow Rigolon,[ab] Paulo César Stringheta,[ab] Evandro Martins,[ab] Seid Mahid Jafari*[cd] and Pedro Henrique Campelo *[ab]

Received 19th June 2025
Accepted 24th November 2025

DOI: 10.1039/d5fb00281h

rsc.li/susfoodtech

This review provides a comprehensive analysis of the sustainable potential of faba beans (*Vicia faba*) as an emerging ingredient in food and biorefinery applications. The study highlights the biorefinery concept as a key strategy to overcome challenges associated with antinutritional factors while maximizing the utilization of faba bean proteins, starches, and fibers. Key physicochemical and techno-functional properties of faba bean components are discussed, alongside their potential applications in food formulations and other industrial sectors. The review also explores the impact of processing methods on the quality and functionality of faba bean-derived ingredients, emphasizing the importance of optimizing extraction and modification techniques. Ultimately, faba beans represent a promising and sustainable source of plant-based ingredients, contributing to circular economy principles and the development of innovative food systems.

Sustainability spotlight

Statement of the problem addressed and originality of the approach. The manuscript addresses the limited use of faba beans in food systems, despite their strong agronomic, nutritional, and environmental advantages. The core problem is the presence of antinutritional factors and the lack of integrated knowledge connecting biorefinery strategies, techno-functional properties, and industrial applications of proteins, starches, and fibers from faba bean. The approach is original because it combines a full biorefinery perspective with detailed physicochemical, nutritional, and processing analyses. This integrated framework is seldom presented in the literature and highlights new routes to valorize faba bean across food, nutraceutical, and bioeconomic sectors. Contribution of the work to create new knowledge in the field. The review synthesizes dispersed evidence into a coherent and actionable model for faba bean valorization. It advances knowledge by clarifying how processing technologies reduce antinutritional compounds while enhancing digestibility and functionality, mapping how protein, starch, and fiber fractions behave under different extraction and modification strategies. It also highlights cultivar-dependent variations, techno-functional behavior of faba bean ingredients, and structural mechanisms that control their performance in foods. The manuscript establishes a scientific basis for ingredient development, enabling the design of improved plant-based formulations and biorefinery processes. Relevance of the work to advance research and impact to the field of food science and technology. The work is relevant for strengthening sustainable food systems and accelerating the transition to plant-based ingredients. By connecting agronomic advantages, biorefinery strategies, and the functional performance of macromolecules, the manuscript supports the development of cleaner, efficient, and economically viable processes for faba bean utilization. The detailed discussion on proteins, starches, and fibers provides guidance for researchers working on alternative proteins, dairy and meat analogs, functional foods, and circular bioeconomy models. The review has strong potential to shape future research directions, especially in ingredient engineering, reduction of antinutritional factors, and the industrial adoption of underutilized legumes.

1 Introduction

Legumes offer excellent agronomic and nutritional benefits; however, their global consumption remains relatively low. This can be attributed to diets that rely on only a few species, such as beans and soybeans, while some legumes are classified as underutilized. Nevertheless, these legumes play a crucial role in mitigating malnutrition and chronic diseases.[1,2] Moreover, they can undergo biorefinery processes, an innovative concept aimed at converting biomass into a wide range of high-value-added

[a]LaCBio, Laboratory of Natural Pigments and Bioactives, Department of Food Technology, Federal University of Viçosa, Viçosa 35570-900, Brazil. E-mail: pedrocampelo@ufv.br
[b]LHMA, Laboratory of Hygiene and Food Microbiology, Department of Food Technology, Federal University of Viçosa, Viçosa 35570-900, Brazil
[c]Department of Food Materials and Process Design Engineering, Gorgan University of Agricultural Sciences and Natural Resources, Gorgan, Iran. E-mail: smjafari@gau.ac.ir
[d]Halal Research Center of IRI, Iran Food and Drug Administration, Ministry of Health and Medical Education, Tehran, Iran

products.[3] Faba bean (*Vicia faba*) is one such example, still underutilized as a food source in various regions despite its rich nutritional profile and significant role in preventing chronic diseases *e.g.*, cardiovascular diseases, cancer, diabetes, and obesity. Additionally, it is useful in the treatment of Parkinson's disease and is recognized as an effective nutraceutical for hypertension control.[4] Its high starch content and absence of cholesterol make it a viable alternative for combating global malnutrition.[5] Furthermore, it is an excellent source of proteins, fibers, minerals, vitamins, and bioactive compounds with health benefits.[4,6–8]

The chemical composition of faba bean (FB) is influenced by factors such as genetics, cultivation practices, soil, and climate, which directly impact the concentration of nutrients and bioactive compounds.[9] These factors determine their applications in the food industry and reinforce their potential for global food security.[6,10] In addition to being underutilized, FB use is restricted due to the presence of antinutritional compounds, such as vicine and convicine.[11,12] To overcome this challenge, biorefinery emerges as an effective alternative, enabling the full utilization of FB and valorization of by-products.[13] This sustainable process, as highlighted by Dragone *et al.*,[3] optimizes resources, reduces waste, and contributes to closing material cycles, strengthening the circular economy and expanding the potential applications of FB in the food, pharmaceutical, and energy sectors.

The aim of this review is to comprehensively analyze the sustainable potential of FB, highlighting biorefinery as a solution to the challenges posed by its antinutrients, as well as exploring the application of FB in the production of proteins, starches, and fibers. Furthermore, we discuss the role of FB in the food industry and related sectors, positioning it as an innovative source of ingredients with nutritional, technological, and sensory benefits.

2 Biorefinery; principles, technologies, and applications in biomass valorization

Augustin & Cole[6] emphasize the urgent need for a radical transformation of the global food system to achieve the United Nations Sustainable Development Goals (SDGs). These goals aim to promote sustainability through environmental preservation and ensure the equitable distribution of food and social policies. Goal 12 stands out by establishing sustainable production and consumption standards, including the implementation of a ten-year plan for the efficient management of natural resources and the reduction of food waste.[14] Ensuring food security while protecting human health and the environment requires fundamental changes. To achieve this, it is essential to foster innovation and develop more sustainable and healthy food systems that balance environmental preservation with fair economic growth.[15,16] Additionally, the transition to a green economy, balancing economic development and environmental conservation, is crucial for long-term adaptation. In this context, integrated management policies that prioritize conservation, efficiency, renewable energy, education, and awareness are essential for the sustainable use of natural resources.[17,18]

Biorefinery is conceptualized as a sustainable system for processing biomass to produce a wide range of marketable bioeconomic products, including ingredients for human and animal food, chemicals, materials, and bioenergy. According to Dragone *et al.*,[3] the concept of biorefinery extends beyond the sustainable conversion of biomass, encompassing its integration into a broader context that incorporates environmental, economic, and social dimensions. Emerging as an economy that offers new practices and opportunities, the development of biorefinery faces challenges that require adaptive strategies to meet new demands and discoveries.[3] In this context, promising opportunities arise in the biological value chains of agricultural and forestry biorefineries, as well as in the bioprocessing of secondary food and agro-industrial streams.[19] The success of this model is contingent upon technological advancement and collaboration between government, industry, and the technological sector, with the goal of structuring production chains that generate economic and social benefits.[20]

Innovation in techniques and technologies is essential for the advancement of biorefineries focused on the circular bioeconomy, aiming to optimize processes and develop new food products.[19] However, the development of food ingredients still occurs in a fragmented manner, hindering sustainable progress. Augustin & Cole[6] emphasize the importance of an interdisciplinary approach that integrates agriculture, nutrition, materials science, and processing, fostering a more efficient and innovative supply chain. According to Lange & Meyer,[19] new trends in biorefining are driven by strategic government investments in partnerships with academia to promote green growth, as well as by commercial incentives. The valorization and processing of secondary streams are essential to ensure the competitiveness and flexibility of traditional large-scale agricultural and food processes, such as those producing starch and plant proteins.

In the case of FB, Karlsson *et al.*[21] emphasize that maintaining FB in animal feed while exploring biorefinery alternatives, such as integrated protein and bioenergy production, can provide substantial environmental benefits. The combination of these alternatives may contribute to reducing greenhouse gas emissions and increase the efficiency of natural resource use, such as water and land. However, the full harvest of FB crops may result in negative impacts on soil health, compromising organic carbon stocks and impairing soil fertility. This can negatively affect the long-term sustainability of agricultural practices. Therefore, FB biorefinery presents significant opportunities for improvement, mainly through the development of more sustainable agricultural practices and technologies that allow for greater nutrient recovery from the soil, promoting more efficient and environmentally responsible exploitation.

In light of the above, it is important to present the essential aspects of FB, *e.g.*, their market characteristics and cultivation, including morphology, distribution, and advantages, in order to fill the gaps in current knowledge on the subject. The focus is also on FB, investigating its antinutrients present, the challenges they impose, and the strategies to mitigate them, aiming to clarify their limitations and solutions. Additionally, the biochemical aspects of the main macromolecules, such as starch, proteins, and fibers, are analyzed, providing crucial information to optimize the utilization of FB, highlighting their potential for biorefinery and future applications.

3 Market and cultivation of faba beans; morphology, distribution, and advantages

FB were identified as early as 7000–8000 BC in Tell el-Kerkh, northwest Syria, and approximately 8000 BC in the southern Levant, standing out as one of the oldest, most diverse, and essential cold-climate food legumes, with high nutritional value. Originating from the Fertile Crescent and the Middle East, it was domesticated millennia ago and is now widely cultivated in various environments around the world as an annual crop.[22–24] Additionally, their culinary versatility and the variety of preparation methods make them a valuable ingredient in food.[4] With an annual production of approximately 4.5 million tons, derived from about 2.5 million hectares cultivated,[25] FB are the fourth most widely grown cold-season legume in the world, ranking behind only peas (*Pisum sativum*), chickpeas (*Cicer arietinum* L.), and lentils (*Lens culinaris* Medik.).

FB has erected, rough stems that can reach heights of 0.3 to 2 m, often with one or more hollow stems at the base, forming a thick growth habit. Its compound leaves are large, containing oval or lanceolate leaflets up to 8 cm in length, giving them a lush appearance. Each cluster can produce 1 to 4 cylindrical pods that are initially green and smooth. The pods are long, curved, and vary in shades of green, providing a fleshy and protective texture for the seeds. These seeds are oval, glossy, measuring 1 to 2 cm in length, and exhibit a variety of colors. Seed size varies significantly within each variety and cultivar, influenced by their position in the pod (Fig. 1). FB varieties show diversity in seed size and coloration, with smaller seeds often used in animal feed and as cover crops, while medium to large seeds are consumed either dry or fresh.[7,26,27]

Unlike most legumes, whose germination is affected by low soil temperatures, FB exhibit high tolerance to these conditions. As one of the few grain legumes adapted to cold climates, its seeds show greater resistance to thermal stress, favoring cultivation in regions with short growing seasons. This species is widely cultivated in various parts of the world, especially in temperate climates, where it thrives in well-drained, nutrient-rich soils. The largest FB-producing countries today are Australia, Brazil, China, France, Germany, India, Indonesia, Japan, Russia, South Korea, the United Kingdom, the United States, Canada, Italy, and Spain, located in diverse regions around the world.[28]

Although sensitive to intense frosts, its planting in the fall is common in regions with moderate winters. However, high temperatures and water deficit can compromise flowering and pod formation, requiring proper management to optimize productivity.[27,29] Displaying wide adaptation to various soil types, FB prefer a pH between 6.5 and 8. In soils with a pH < 5.5, the ability to fix atmospheric nitrogen is compromised, negatively impacting production. Among the legumes cultivated in the fall-winter season, FB exhibit the highest tolerance to excess water in the soil. However, waterlogging during the flowering phase can negatively affect yield, causing persistent effects even after soil drainage. The ideal sowing period varies according to climate, being in the fall for moderate climates and in late winter or early spring for colder regions. In Mediterranean regions, they are planted at the end of summer and harvested in the fall[22–24,30]

With a rapidly growing global market in recent years, FB are widely cultivated across all inhabited continents. However, this

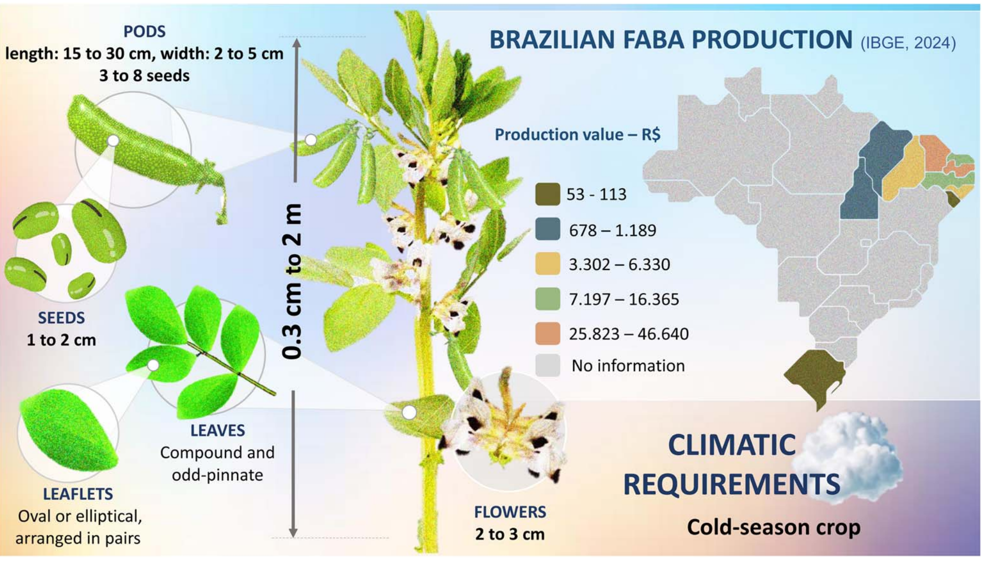

Fig. 1 Faba bean characterization; morphology, national productivity (base year 2023), and climate requirements.

growth is subject to variations influenced by factors such as climatic conditions, commercial demand, agricultural policies, and technological advances in the production sector.[10] According to recent estimates, the global FB market value increased from USD 3.06 billion in 2020 to USD 3.18 billion in 2021, with a compound annual growth rate (CAGR) of 3.77%. This growth is primarily driven by the rising demand for natural and plant-based proteins. Projections indicate that the market will expand from USD 3.41 billion in 2023 to USD 3.51 billion in 2024, with a CAGR = 2.9%, reaching USD 3.47 billion in 2025, with a CAGR = 2.19%, and USD 4.09 billion by 2028, with a CAGR of 3.9%.[28,31] Between 2023 and 2032, a significant increase in FB market is forecasted, with estimates pointing to an increase in market value from 8.9 million tons in 2023 to 12.5 million tons in 2032. This represents a global CAGR = 3.9%.[32]

The projected growth in FB market is driven by several factors, including the increasing interest in sustainability and eco-friendly production methods, the growing adoption of plant-based fermentation processes, consumer preference for natural products and clean labels, the expansion of export opportunities, and the ongoing trend towards plant-based diets. Future key trends are expected to include the development of innovative fermented ingredients, an increased focus on personalized nutrition, greater attention to probiotics and gut health, the growth of artisanal fermentation practices, and continuous technological advancements in the industry.

In 2022, Brazil recorded a production of 12 061 tons of FB, cultivated on an area of 35 609 hectares, with an average yield of 339 kg per hectare, resulting in an estimated production value of 90 396 thousand reais.[33] However, updated data from IBGE[34] indicates a decrease in production indicators compared to the previous year. The variation in productivity can be attributed to several factors, including growing conditions, adopted agricultural practices, and the varieties cultivated. In 2023, FB production was 10 372 tons, with a harvested area of 33 153 hectares, an average yield of 313 kg per hectare, and an estimated production value of 82 454 thousand reais. Table 1 presents the states responsible for FB production.

FB plays a key role in agriculture, contributing to increased soil fertility and promoting sustainable farming practices. Its biological nitrogen fixation capacity is remarkable, surpassing other legumes such as peas and lentils.[35–37] Furthermore, its wide adaptability allows for cultivation in various climatic conditions, making it a versatile crop in different regions.[35,37] The cultivation of FB may play an important role in pest control, as its plant characteristics attract a wide variety of predators and parasitoids.[38] Additionally, its complex structure may favor the presence of arachnids, raising the hypothesis that FB could increase the density of arthropods acting as natural biological control agents, even as an annual monoculture. Therefore, it is suggested that proper management of its habitat could enhance ecosystem services related to natural biocontrol.[4,10,38]

With rapid growth and high biomass production, FB stands out for its tolerance to stress caused by trace elements, positioning it as a promising candidate for phytoremediation. Phytoremediation is a technique used for the removal, immobilization, or degradation of contaminants from soil and water, minimizing environmental impacts and health risks. When incorporated into crop rotation systems, FB becomes a valuable tool for farmers seeking more sustainable agricultural practices. In addition to increasing the yield of subsequent crops and reducing the environmental footprint, it contributes to improving soil fertility when grown in mixed cropping systems, enabling its efficient combination with other crops.[4,36] According to Mexe *et al.*,[29] the incorporation of FB into crop rotation systems not only promotes diversification but also plays a significant role in optimizing farm management. With relatively low installation costs and considerable potential to improve soil quality, the crop emerges as an attractive alternative from an economic perspective. It is highlighted that its interaction with nitrogen-fixing bacteria allows cultivation without the need for nitrogen fertilization.[35,39]

Agroforestry, which involves the simultaneous cultivation of two or more crops, is an efficient strategy to optimize the use of resources such as water, nutrients, light, and temperature, promoting plant growth and productivity. Additionally, this practice fosters beneficial interactions between crops and soil microorganisms, creating more favorable conditions for plant development.[40] When grown in association with cereals, tubers, and vegetables, FB enhance the quality of food crops, as they have the ability to improve soil health.[35,39] According to Marcos-Pérez *et al.*,[41] even with a 30% reduction in fertilizer application, the presence of FB in the intercropping system contributes to an increase in the total nutrient production, regardless of the

Table 1 Faba bean production in Brazilian states in 2023 (IBGE, 2023)

State	Production value (R$)	Quantity produced (tons)	Harvested area (hectares)	Average yield (kg per hectare)	Largest producing city
Ceará	26.996	3.514	14.695	239	Tarrafas – CE
Paraíba	25.948	3.260	9.231	353	Alagoa Grande – PB
Pernambuco	11.694	1.405	4.082	344	Surubim – PE
Rio Grande do Norte	6.257	669	1.854	361	Tenente Laurentino Cruz – RN
Piauí	5.512	661	1.965	336	Tanque do Piauí – PI
Alagoas	2.992	541	500	1.082	Boca da Mata – AL
Maranhão	1.482	190	672	283	Passagem Franca – MA
Tocantins	1.387	94	101	931	Centenário – TO
Sergipe	134	26	46	565	Pacatuba – SE
Rio Grande do Sul	51	12	7	1.714	Venâncio Aires – RS

cultivation model adopted. Thus, they become an essential component in the sustainable intensification of agricultural systems, contributing to the improvement of biodiversity, ecosystem services, and the reduction of dependency on nitrogen fertilizers in food production.[37,39]

4 Antinutrients in faba bean; challenges and reduction strategies

Pereira *et al.*[42] highlight that, with the increasing interest in diversifying diets through the consumption of food crops, it is essential to understand the bioavailability of nutrients from plant foods during digestion, also considering the effects of antinutritional compounds. Although antinutrients are often seen as harmful, a balanced intake of these compounds can actually bring health benefits, especially in the context of nutraceutical and functional properties. In order for these benefits to be realized, it is crucial to adopt proper processing techniques that reduce the formation of undesirable compounds.

FB are an excellent source of proteins, fibers, minerals, vitamins, and bioactive compounds that offer various health benefits.[4,6–8] However, their use has been limited due to the presence of antinutritional factors, typical of legumes. Among these compounds, notable ones include trypsin inhibitors, lectins, phytic acid, saponins, condensed tannins, as well as the pyrimidine glycosides vicine and convicine, which are concentrated in the cotyledons of the seeds, both fresh and dried.[11,12] Chemically, vicine is defined as 2,6-diamino-4,5-dihydroxypyrimidine-5-(β-D-glucopyranoside), and convicine as 2,4,5-trihydroxy-6-aminopyrimidine-5-(β-D-glucopyranoside).[43] Due to their adverse effects, several studies have aimed to modify their biosynthesis in order to reduce or eliminate the presence of these antinutrients.[11,12]

The concentration of vicine and convicine in fresh or dry faba seeds is influenced by their interaction with other constituents, especially starch and protein, which are predominant in their composition. Additionally, environmental factors play a significant role in the variation of these compounds, leading to differences between cultivars and growing years. Despite advancements in the development of varieties with up to a 90% reduction in concentration, complete elimination has not yet been achieved.[12,43] The levels of vicine and convicine in different FB-derived products are shown in Table 2, highlighting variations related to the treatments applied and the varieties used. Accordingly, treatments such as sonication have a significant impact on reducing the levels of vicine and convicine, which is relevant for improving the nutritional quality and reducing the antinutritional effects of FB. Additionally, the variations between different varieties emphasize the importance of selecting those with lower concentrations of these compounds, whether for food consumption or industrial applications.

These antinutrients are hydrolyzed by a native β-glucosidase, resulting in the formation of the aglycones divicine and isouramil. The ingestion of vicine and convicine, present in FB, can cause favism in individuals with a genetic deficiency of glucose-6-phosphate dehydrogenase (G6PD) in erythrocytes (Fig. 2), leading to hemolytic anemia, which can be fatal. Furthermore, these compounds have been shown to decrease feed efficiency in monogastric animals. In parallel, some strategies are exploring to remove these components from food matrices. This process aims to enable the development of protein isolates and derivative products free from these antinutrients, allowing for their broader and safer application in the food industry.[12,26]

According to Khazaei *et al.*,[12] a faba line with low levels of vicine and convicine was identified in the 1980s and incorporated into modern cultivars, being considered safe for individuals with G6PD deficiency. A robust molecular marker now enables assisted selection to reduce these compounds. However, its biosynthetic pathway is still not fully elucidated and remains under investigation. It is worth noting that a coordinated international effort has been advancing this understanding, which could lead to even greater reductions or even the elimination of these substances. In response to these challenges, the elimination of vicine and convicine has been

Table 2 Content of the main pyrimidine glycosides (vicine and convicine) in faba products

	Pyrimidine glycosides		
Products	Vicine	Convicine	References
Raw flour	4.92 (mg per g DM)	3.91 (mg per g DM)	44
Native protein	3.80	—	
Sonicated protein (5 min)	3.67	—	
(10 min)	3.58	—	
(15 min)	3.58	—	
(30 min)	3.64	—	
(45 min)	3.64	—	
(60 min)	3.56	—	
Protein isolate	—	0.30 (mg per g DM)	45
	2.18 (mg per g DM)	1.52	
Flour from the Alexia variety	5.647 ($\mu g\ g^{-1}$)	2.032 ($\mu g\ g^{-1}$)	2
Flour from the Boxer variety	6.818	2.707	
Flour from the Glória variety	7.014	1.906	

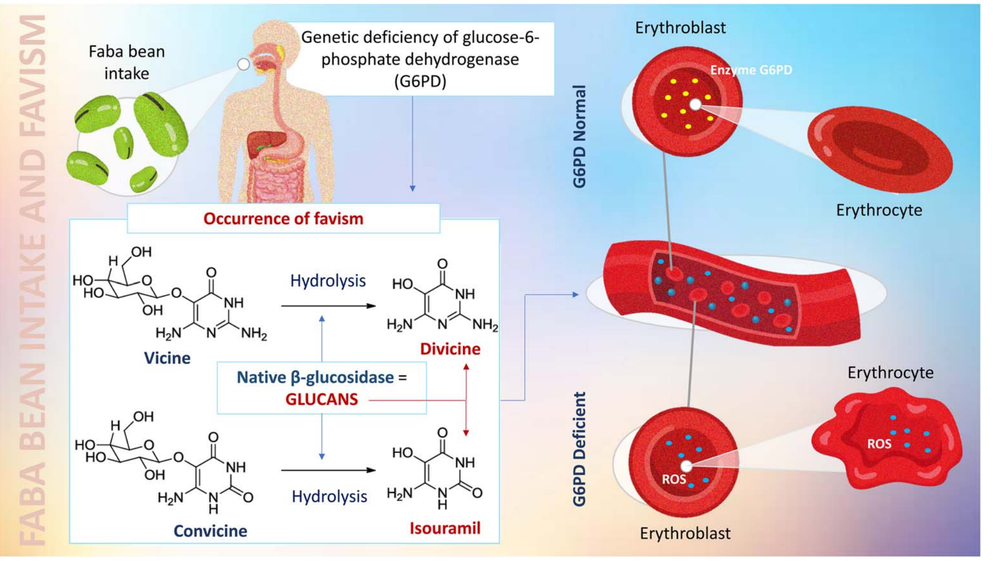

Fig. 2 Action of vicine and convicine in the human body: Favism.

a central goal in FB genetic improvement programs worldwide. Recently, the development of cultivars with low levels of these antinutritional glycosides has represented a significant advance, expanding the safe usage possibilities of this legume. This progress is particularly meaningful, as it allows FB to be more widely used in human and animal food, mitigating the risks associated with the consumption of these toxic compounds.[12,26,46,47] It is important to note that the higher initial costs of these lines are associated with investments in research and genetic improvement, as well as expenses related to the production of seeds for specific varieties.[12]

To enhance the nutritional value of FB and make it more suitable for consumption, various methods are applied to reduce its antinutritional factors. Among the main techniques used are peeling, soaking, cooking, autoclaving, germination, extrusion, fermentation, and enzymatic treatment (Fig. 3). According to Pereira *et al.*,[42] soaking in distilled water or an acidic solution stands out for reducing undesirable compounds, such as convicine. Thermal cooking improves protein digestibility and reduces antinutrients, with autoclaving proving to be more efficient than traditional boiling. Extrusion, a high-shear and short-time technique, significantly contributes to the reduction of antinutritional factors and enhances the sensory properties of the food. Fermentation is also an effective method, as it promotes the hydrolysis of antinutrients through microbial action. In this context, the use of microorganisms such as *Lactobacillus bulgaricus* and *Bacillus subtilis* has shown good results in eliminating these undesirable compounds. In

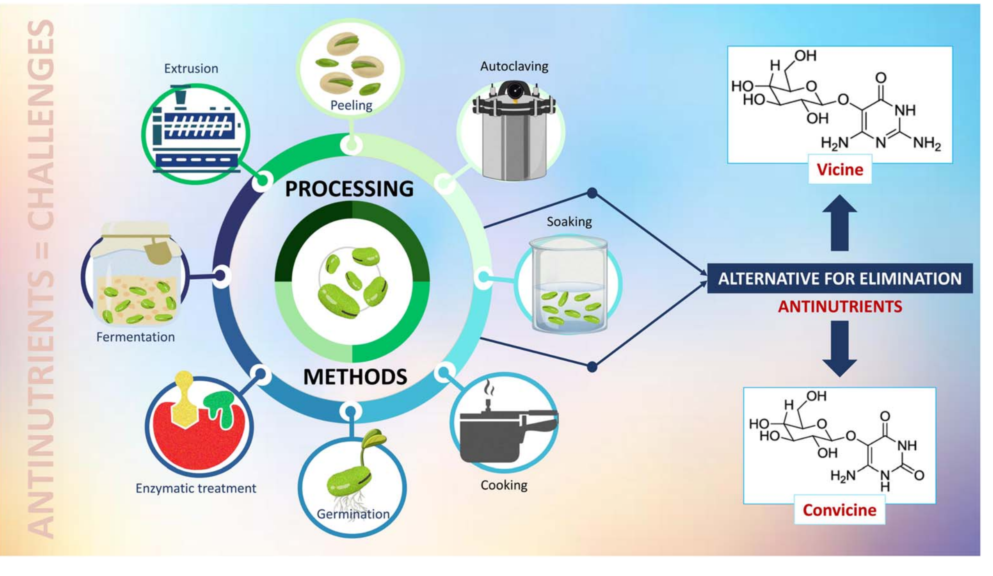

Fig. 3 Most common industrial processes for reducing antinutritional factors in faba products and by-products.

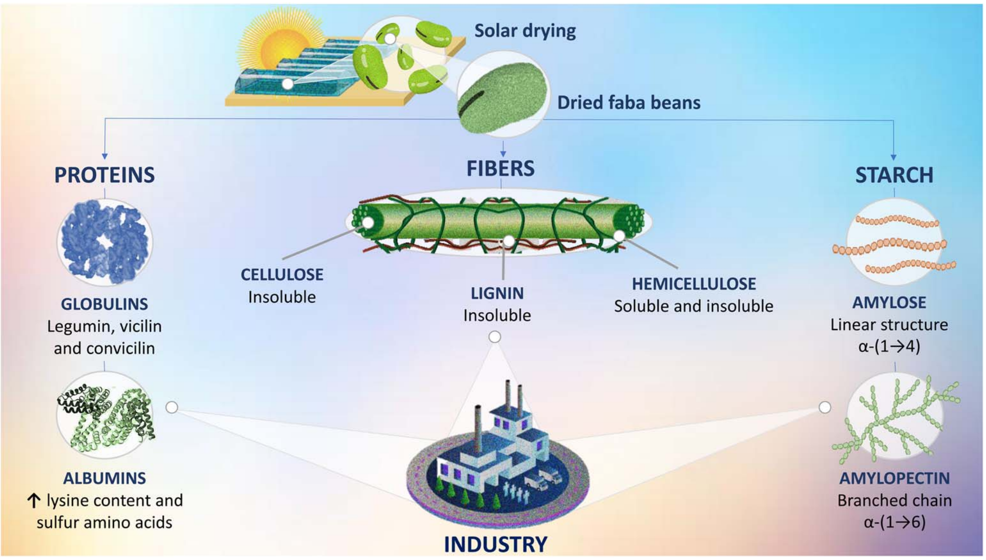

Fig. 4 Concept of faba bean biorefinery as a means of developing new food ingredients for industrial applications.

addition to these strategies, Pereira *et al.*[42] also highlight the importance of gamma irradiation, which helps reduce trypsin inhibitors, phytic acid, and oligosaccharides associated with flatulence, as well as dielectric heating, performed by microwave or radiofrequency, which contributes to the reduction of tannins, saponins, and phytic acid while improving protein digestibility.

Lu *et al.*[48] studied the extraction of wet protein from dry FB with the goal of minimizing antinutritional factors, applying response surface methodology. To overcome the limitation of the presence of antinutritional compounds, the researchers developed an extraction method based on an aqueous alkaline process followed by isoelectric precipitation with different salt concentrations. This procedure resulted in the extraction of 15.8 g protein/100 g flour, with a protein content >83% in the final extract. Moreover, the technique proved effective in reducing antinutrients, lowering phytic acid (28.0%) and lectin (87.5%) levels. It is worth noting that the protein extraction resulted in a significant reduction of vicine and convicine in FB flour. While the flour contained 1238 $\mu g\ g^{-1}$ of vicine and 37.9 $\mu g\ g^{-1}$ of convicine, in the protein isolate, these values dropped to 19 $\mu g\ g^{-1}$ and <1 $\mu g\ g^{-1}$, corresponding to reductions of 98.5% and 99.7%, respectively.

Tuccillo *et al.*[49] identified that vicine and convicine are associated with unpleasant flavors, with their derivatives being responsible for bitterness, although this relationship has not been extensively investigated. It is highlighted that the presence of free phenolics, along with these compounds, has been linked to intense residual flavors, bitterness, and a dry mouthfeel. Furthermore, lipid oxidation products have been associated with pea, cereal, and unpleasant odors and flavors. Based on this, it provides an additional reason for controlling these compounds. After removal during processing, FB can be used in a wide range of protein-rich products, offering a sustainable alternative to animal-derived protein sources, in line with current consumption trends.[50]

5 Proteins of faba bean

Fig. 4 illustrates the process of converting dried FB seeds into grains, which, after undergoing biorefinery processes, are transformed into high-value macromolecules such as protein isolates, fibers, and starch. FB are a promising source of plant-based protein due to their high concentration of native protein, making them economically viable for the production of protein derivatives.[51] Their protein fractions exhibit differences in amino acid (AA) composition, physicochemical properties, and molecular weight. Among these fractions, the salt-soluble globulin, which accounts for 40–50% of the total seed protein, is particularly notable, along with the water-soluble albumin (12–16%), prolamin (2–4%), and the alkali-soluble fraction (20–30%).[52,53] According to Table 3, significant variations in AA profile of the Alexia, Boxer, and Glória FB varieties highlight the importance of selecting the variety for food applications aiming for an optimized protein profile.

According to Oluwajuyitan & Aluko,[54] the protein fractions of albumin, globulin, and glutelin from FB contain a variety of AAs, including: hydrophobic (alanine, valine, isoleucine, leucine, tyrosine, phenylalanine, tryptophan, proline, methionine), positively charged (histidine, lysine), negatively charged

Table 3 Amino acid content in different faba bean varieties.[2]

	Varieties of faba beans		
Amino acids	Alexia	Boxer	Glória
Histidine	28.2	33.6	31.0
Isoleucine	23.4	33.1	25.8
Leucine	55.0	72.1	58.0
Lysine	49.7	65.4	52.4
Phenylalanine	30.5	36.6	33.3
Threonine	28.6	37.3	32.1
Valine	26.0	42.3	38.4

(asparagine, glutamine, and glutamic acid), aromatic (phenylalanine, tryptophan, and tyrosine), sulfur-containing (cysteine and methionine), and branched-chain AAs (valine, isoleucine, leucine). Additionally, FB is rich in essential AAs *e.g.*, histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine. The main storage proteins, such as glycinin, phaseolin, and vicilin, are predominantly located in the cotyledon and embryonic axis of the seeds.[5] In FB, the proteins are divided into two main fractions: globulins, which account for >80% of these fractions, composed of legumin, vicilin, and convicilin, known as 11S and 7S based on their sedimentation coefficients in ultracentrifugation. Additionally, albumins present a balanced nutritional profile, characterized by a high content of lysine and sulfur-containing AAs such as methionine and cysteine.

With its richness in lysine and other essential nutrients, FB stands out as a significant source of nutritional compounds. Additionally, it contains levodopa (L-DOPA) a precursor to dopamine, which holds potential as a bioactive compound for the treatment of Parkinson's disease.[50] This protein composition is essential in determining the nutritional and functional quality of FB as a source of plant-based protein.[10,55] Warsame *et al.*[55] analyzed different FB genotypes and identified over 100 proteins, highlighting its complex proteome. Mass spectrometry revealed that most of the analyzed bands contained multiple protein types, including 15 polymorphic bands with variations in the α-subunits of legumin. Rare subunits of 36 and 40 kDa were detected in the genotypes LG Cartouche and NV657, respectively, and were classified as legumin type B and type A. These variations may influence the genetic composition, nutritional quality, and processing of seed protein. In addition to storage proteins, other functional classes were identified, such as lipoxygenase, heat shock proteins, sucrose-binding proteins, albumin, and defensins.

The functional properties of a protein are directly dependent on its 3D conformation, which can be altered by physical, chemical, or biological interventions. These structural changes result in significant modifications in its functionalities. Processes such as partial denaturation and controlled aggregation are used to improve the solubility, thermal stability, foam formation, and emulsification of plant proteins.[46,47,56] The 3D structure of proteins is fundamental to their biological functions, and any alteration can significantly impact their activity and effectiveness. These modifications can influence the protein's interaction with other molecules, its ability to catalyze specific chemical reactions, or its affinity for receptors in target cells. Depending on the desired application, these changes can impart distinct characteristics to the final products, adding value to them.[10,57]

The breaking of disulfide bonds in FB proteins involves the rupture of covalent links between sulfur atoms present in these proteins. This phenomenon can be triggered by various conditions, such as changes in pH, temperature, or enzymatic action, resulting in alterations in the structure and functional properties of FB proteins. Understanding this process is crucial for controlling the properties of FB proteins in various applications, such as in the food industry and biotechnology.[10,57] Solubility and water-holding capacity are essential indicators of protein quality, particularly as functional food ingredients. The isoelectric point of FB proteins is approximately pH 4.0, where their solubility is minimal. However, as the pH increases, the solubility of the proteins gradually increases, reaching its maximum around pH 8.0.[46,47,56]

The physicochemical and techno-functional properties of proteins extracted from FB make them suitable for various applications in the industry. However, compared to soy proteins, they tend to have lower solubility and gelling capacity. These characteristics are directly related to the type of protein, its chemical composition, AA sequence, and secondary and tertiary structures.[56,58] The foaming properties of protein preparations, derived from their chemical structure, represent a relevant functional characteristic.[59] The increasing presence of plant-based protein products in the global market highlights the potential of FB products to significantly contribute to this market.[10]

The ability of proteins to influence the texture and sensory properties of final products is a key factor. In the case of FB proteins, their use is determined by their emulsifying and foaming properties, as well as their ability to form gels.[60,61] Various technologies have been developed for the use of FB whole flour and its enriched fractions. Among these, starch and protein concentrate stand out, obtained through dry fractionation and air classification, as well as the protein isolate, produced by wet fractionation. These ingredients are employed in the production of dairy analogs, meat, and other foods and products. However, challenges related to taste, odor, and texture remain, and their causes are currently being investigated.[10] Plant proteins have relatively limited functionality compared to animal-based proteins, which can restrict their applications in various food products. This factor must be considered when developing new formulations.[56] Additionally, the use of technologies capable of modifying their structures can enhance their techno-functional characteristics and address the challenges faced in using plant proteins as ingredients in food products.[50]

Table 4 presents studies that have evaluated FB proteins, including their extraction process, components, and techno-functional characteristics. Badjona *et al.*[44] emphasize that the reduction of pyrimidine glycoside levels suggests that aqueous extraction could be crucial for obtaining higher protein purity. On the other hand, Krause *et al.*[45] (2023) noted that the proteins exhibited larger size and lower water solubility, which contributes to their optimal digestibility and high foam stability. Due to the low solubility, the most suitable applications for these proteins would be in solid matrices, such as alternatives for baked goods. Krause *et al.*[45] reported that the analyzed proteins are smaller in size and have a high foam formation capacity, although with lower digestibility. These characteristics make them promising for use in plant-based beverages that are both foamy and protein-rich. The functionality of the proteins is also influenced by the purity of the protein fraction.[62] The authors highlighted that the protein composition of FB affects the textural properties of gels, with gels formulated from protein isolates showing significant differences compared to those

Table 4 Faba proteins, their extraction methods, components, and techno-functional characteristics[a]

Product	Protein (g/100 g DM)	Method of extraction	Protein composition	Additional information	*D* (%)	PS (%)	WHC (%)	OBC (%)	FC (%)	FS (%)	References
Protein isolate	83.56	The standard procedure of alkaline isoelectric precipitation	Globulins (70–78%) Albumins (10–20%)	It identified vicilin, legumin, albumin, sucrose-binding protein, and lipoxygenase, with three main protein bands (45, 35, and 20–25 kDa). Vicilin was found at approximately 35 and 47–50 kDa, while legumin appeared at 20–25 kDa	—	—	—	—	—	—	44
	72.64	Isoelectric precipitation at pH = 3.5 or lower. The precipitate reincorporated, subjected to low-temperature pasteurization at 50–80 °C, and then spray-dried	Globulins	Convicilin (∼55 kDa), legumin (∼40 kDa and ∼20 kDa), and vicilin (∼30 kDa)	23.30	pH: 7 9.49	149.80	65.32	18.06	70.00	45
	71.37	Membrane filtration from the soluble fraction after PI 1 precipitation, spray-dried	Albumins	Smaller proteins (7–10 kDa)	9.59	pH: 7 96.04	No analysis performed	229.13	133.33	39.79	
	77.28	Isoelectric precipitation	—	—	—	—	—	—	—	—	62
Raw flour	27.5	Raw faba seeds, soaked and germinated, were ground into flour *via* a two-step process: (i) "pre-breaking", seeds crushed into coarse grains using a lab disk mill. (ii) "pin mill", these grains refined in a pin mill to obtain fine flours	—	—	78.6	78.1	47.7	53.8	107.8	21.1	63
Soaked flour	28.4				78.7	78.3	47.2	54.2	110.1	20.4	
Germinated flour (24 h)	27.4				79.6	78.2	49.8	55.7	122.8	19.4	
(48 h)	27.6				79.8	78.9	49.4	55.9	132.7	17.5	
(72 h)	28.0				79.9	79.7	50.2	56.3	137.8	16.4	
Flour from the Alexia variety	22.7	Fifteen cultivars of faba (*Vicia faba* L., var. minor) harvested at the mature stage, and after drying, the seeds were ground into fine flour using a rotor mill with a 0.5 mm sieve	—	—	—	—	—	—	—	—	2
Boxer variety	25.8										
Glória variety	28.3										

[a] *D* = digestibility; PS (%) = protein solubility; WHC = water-holding capacity; OBC = oil-binding capacity; FFC = foam formation capacity; and FS = foam stability.

made from blends, even when the solid content is kept constant.

Regarding FB flour, it stands out for its high protein content, reaching 27.5% in its raw form, a value higher than that of yellow pea flour.[63] However, its protein matrix is strongly associated with starch and fiber, which makes digestion more difficult. While germination does not significantly alter the protein composition, it increases α-amylase activity, which can modify protein solubility and influence their functional properties. Additionally, studies show substantial differences between cultivars in terms of nutrients and antinutrients, directly impacting the bioavailability of nutrients.[2] Therefore, the nutritional gain from FB varies depending on the cultivar used, a crucial factor for optimizing its use in different food application.

6 Starches in faba bean

Starch is the main component of FB, constituting between 22% and 45% of the seed.[64,65] It is primarily composed of two polymers: amylose and amylopectin. These two polymers, formed by repeated units of glucose linked by glycosidic bonds, account for approximately 98–99% of starch by dry weight.[66] Amylose consists of α-(1 → 4) D-glucopyranosyl units, while amylopectin is made up of branched chains of glucans, with branching occurring through α-(1 → 6) linkages at the reducing ends. The ratio between amylose and amylopectin, as well as the presence of minor starch components, varies depending on the botanical origin and variety of legumes.[67]

It is important to highlight that the methods currently used to quantify amylopectin may present inaccuracies, indicating the need for more refined and reliable approaches.[66] The structure of amylopectins in FB starch shows a lower proportion (21.5%) of branched chains with a degree of polymerization (DP) between 6 and 12, in contrast to a higher proportion (56%) of branched chains with a DP = 13–24. The average length of the branched chains in amylopectins is approximately 20.4 (DP).[68]

Sofi *et al.*[69] observed a wide variety of shapes in FB starch granules, including oval, round, elliptical, and irregular forms, characterized by the presence of cavities on their surfaces. The polymorphic structure of starch can be categorized into three main forms: A, B, and C. While type A polymorphs are predominant in cereal starches, type B polymorphs are more common in starches from tubers and cereals with high amylose content. Type C polymorph, a mixture of types A and B, is considered intermediate and is commonly found in starches from legumes.[70] FB-derived starch is a complex macromolecule widely used due to its versatility, playing an important role not only in the food industry but also in various industrial sectors. Its functionality can be enhanced through physical, chemical, and enzymatic modifications.[67] It shows limited solubility and restricted swelling, but greater solubility at intermediate temperatures compared to cereal starches. Its structure features longer branched amylopectin chains and a type C polymorphic arrangement, which significantly contribute to its functional properties and the final product quality. FB starch stands out as an excellent substitute for industries traditionally reliant on corn starch.[65,69] Despite its potential, research on FB starch remains limited, and the exploration of new methods could reveal even broader industrial applications. Its physicochemical properties, such as amylose leaching, swelling, and solubility, vary depending on the integrity of the starch and the presence of fissured granules. Additionally, the granules exhibit a relatively low leaching temperature range, suggesting significant leaching, possibly due to weaker molecular interactions.[67]

The exact effects of storage temperature on the starch structure are not yet fully understood. These structural changes reflect the complexity of FB starch and its relationship with the grain composition. Furthermore, FB starch exhibits relevant physicochemical properties, such as a pH of 7.23, water absorption capacity of 1680 g kg^{-1}, oil absorption capacity of 1790 g kg^{-1}, and an apparent density of 0.95 g L^{-1}.[69] The extraction of FB starch presents a high amylose content (33.55%), which has a direct impact on fundamental properties such as gelatinization, retrogradation, and resistance to enzymatic digestion. The type C crystalline pattern, characteristic of this starch, influences its solubility and swelling capacity, essential factors for determining its applications in products that require greater thermal stability and resistance during processing. These properties make FB starch a promising alternative in various fields, including the food and pharmaceutical industries, where the modulation of these characteristics is crucial for the development of products with optimized performance.[71] It is essential to emphasize the classification of starches based on their degradation rate in the intestine and subsequent glucose absorption into the bloodstream: rapidly digestible, slowly digestible, and resistant starch. Both rapidly and slowly digestible starch are completely digested in the small intestine; however, slowly digestible starch is processed at a slower rate.[72] The consumption of rapidly digestible starch leads to a rapid increase in blood glucose levels due to its quick digestion.[64]

Regarding enzymatic digestion resistance, FB starch exhibits low proportions of rapidly digestible starch and a predominance of resistant starch. It is known that structural factors, *e.g.*, the starch source and amylose content, influence its digestibility, while cooking has less impact. However, post-cooking storage, particularly drying, further reduces digestibility, resulting in lower hydrolysis rates and an increase in resistant starch associated with fiber. These findings highlight the complexity of FB starch digestion and its potential impact on health.[64,66,67] Moussou *et al.* (2019) support this topic, presenting results in which FB have high levels of non-amylose polysaccharides, with an average of 172.26 mg g^{-1}. It highlights that the digestibility of starch in FB flour was slower compared to other legumes, showing a higher content of slow-digesting starch and a lower content of resistant starch. Therefore, FB have significant potential as a nutritious and healthy food ingredient. Table 5 provides detailed information on the properties of FB starch.

According to Zhang *et al.*,[71] FB starch requires more energy for gelatinization due to its high crystallinity. This increase in crystallinity results in a broader gelatinization temperature range and a higher gelatinization enthalpy. On the other hand,[68] reported lower crystallinity and gelatinization enthalpy, implying a faster and more efficient gelatinization process. Additionally, this isolated starch exhibited reduced pasting

Table 5 Studies that evaluated faba bean starch, its components, and physicochemical characteristics[a]

Product	Starch content (%)	Polymer content		AM (%)	AR (%)	GC (%)	PE (%)	S (%)	TL (%)	G	FAR	PC	D		References
		AML (%)	AMP (%)										Raw	Cooked	
Starch isolate	96.64	33.55	—	—	—	18.50	50 °C: 1.09 60 °C: 1.13 70 °C: 6.85 80 °C: 10.29 90 °C: 12.67 —	50 °C: 2.29 60 °C: 2.71 70 °C: 6.67 80 °C: 8.18 90 °C: 9.92 —	0 h: 3.84 12 h: 2.74 24 h: 2.25 36 h: 1.65 48 h: 1.18 60 h: 1.05 72 h: 0.83	T_o (°C): 61.96 T_p (°C): 66.38 T_c (°C): 73.06 ΔT_r (°C): 11.09 ΔH (J g^{-1}): 6.68 —	—	PV (cP): 3.524 TV (cP): 2.277 BD (cP): 1.247 FV (cP): 4.814 SB (cP): 2.536 PT (min): 4.2 GT (°C): 70.2	—	—	71
	965	39.9	DP 6–12: 21.5 DP 13–24: 56.0 DP 25–36: 12.8 DP > 36: 9.7	0.9	—	—	—	—	—	T_o (°C): 58.9 T_p (°C): 64.2 T_c (°C): 72.1 ΔH (J g^{-1}): 12.4	T_o (°C): 45.8 T_p (°C): 58.5 T_c (°C): 73.8 ΔH (J g^{-1}): 6.5	—	RDS: 15.3% SDS: 34.5% RS: 46.7%	RDS: 88.1% SDS: 2.5% RS: 5.9%	68
	86.43	—	—	—	8.1	—	—	—	—	—	—	—	—	—	62
Flour with high starch content	44.1	31.4	DP 6–12: 25.1 DP 13–24: 59.0 DP 25–36: 10.9 DP > 37: 5.1	—	—	—	—	—	—	—	—	—	—	RDS: 82.97% SDS: 10.51% RS: 6.51%	73
	60.3	33.1	DP 6–12: 24.0 DP 13–24: 60.3 DP 25–36: 11,2 DP > 37: 4.4										—	RDS: 83.04% SDS: 9.93% RS: 7.03%	
Raw flour	43.3	18.6	—										RDS: 4.7% SDS: 12.4% RS: 37.2%	RDS: 2.6% SDS: 3.00% RS: 78.00%	
Soaked flour	44.0	17.1	—	—	—	—	—	—	—	—	—	—	RDS: 5.00% SDS: 17.5% RS: 21.6%	RDS: 3.00% SDS: 3.9% RS: 77.8%	63

Table 5 (*Contd.*)

Product	Starch content (%)	Polymer content: AML (%)	AMP (%)	AM (%)	AR (%)	GC (%)	PE (%)	*S* (%)	TL (%)	G	FAR	PC	*D*: Raw	Cooked	References
Germinated flour (24 h)	44.8	19.8											RDS: 8.3% SDS: 21.5% RS: 15.00%	RDS: 3.6% SDS: 3.2% RS: 78.4%	
Germinated flour (48 h)	42.9	17.6											RDS: 9.3% SDS: 22.00% RS: 11.6%	RDS: 1.5% SDS: 2.3% RS: 78.6%	
Germinated flour (72 h)	42.9	19.4											RDS: 9.9% SDS: 23.7% RS: 9.3%	RDS: 1.6% SDS: 1.4% RS: 80.4%	

[a] AML (%) = amylose; AMP (%) = amylopectin; DP = degree of polymerization; MS (%) = modified starch; RS (%) = resistant starch; GC (%) = crystallinity degree; EP (%) = expansion power; *S* (%) = solubility; LT (%) = light transmittance; G = gelatinization (T_O: onset temperature; T_P: peak temperature; T_C: conclusion temperature; ΔT_r: gelatinization temperature range; ΔH: gelatinization enthalpy); RSF = retrograded starch fusion = (T_O: onset temperature; T_P: peak temperature; T_C: conclusion temperature); PC = pasting properties (PV: peak viscosity; TV: trough viscosity; BD: breakdown; FV: final viscosity; SB: setback; PT: peak time; GT: pasting temperature); digestibility = (RDS: rapidly digestible starch, SDS: slowly digestible starch, RS: resistant starch).

viscosity but a high gelation capacity, favoring the formation of firmer and more stable gels. This characteristic makes FB starch particularly interesting for applications in food products, *e.g.*, gelatin substitutes and thickeners, as well as a promising alternative for industries seeking ingredients with good gelation and texturization properties. Johansson *et al.*[62] observed that the substitution of protein with starch reduced gel fracture stress and deformation. In the analyzed gels, protein formed the continuous phase, while starch granules were dispersed throughout the matrix. These changes in textural properties were influenced by water adsorption and the structural reinforcement provided by the protein components. Additionally, Gangola *et al.*[73] reported that adding FB flour and starch isolate increased the concentrations of protein and starch, altering the structure of amylopectin. The *in vitro* digestibility of starch was influenced by glucan chains, with short chains promoting digestion, while medium and long chains reduced digestibility.

Setia *et al.*[63] highlight that starch in FB flour makes up 43.3% of its raw composition, with digestibility lower than that of yellow pea flour due to its association with proteins and fibers. During cooking, digestibility increases significantly through gelatinization, which facilitates the hydration and breakdown of starch. This process also alters the viscosity and texture of the flour, affecting its application in food products. Digestibility varies depending on the cultivar, cooking conditions, and interaction with other components of the food matrix, making it essential to understand these modifications to optimize its use in food formulations. Suárez-Diéguez *et al.*[74] developed and optimized a lab process to obtain resistant starch from FB, using a retrogradation technique to increase its content. This study demonstrated that FB starch can be a potential functional ingredient due to its reduced and slower digestibility.[50] Among the techniques, wet milling is the most common method for starch extraction, with yields ranging from 33% to 48%. FB starch has a high resistant starch content (46.7%), low levels of rapidly digestible starch (15.3%), and slowly digestible starch (34.5%).[75] Additionally, it has low solubility (9.92 g/100 g) and swelling power (12.67 g g^{-1}), due to the strong bonding forces between the granules.[71]

Studies on the rheology of legume starches indicate textural and solubility variations, influenced by composition and granular structure.[66,71] FB starch shows an increase in swelling with temperature, followed by a reduction above 85 °C, a behavior associated with its amylose content and the semicrystalline structure of the granules.[71] The moderate viscosity of FB starch places it between corn starch, which forms thicker pastes, and wheat and pea starches, which have lower thickening capacities. Additionally, its lower solubility and greater thermal stability, compared to other legume starches, give FB starch potential for industrial applications that require shear resistance and control over retrogradation. In this context, it stands out as an intermediate alternative, ideal for products that require moderate consistency, thermal stability, and balanced properties of gelatinization and retrogradation.[71] Among the notable characteristics of FB starch, its high degree of crystallinity stands out, requiring more energy for gelatinization.[71] The high gelatinization temperature, viscosity during pasting, rapid retrogradation, gel elasticity, and relatively low digestibility are attributed to its high amylose content.[65] Studies on legume starches highlight gelatinization as an essential process in thermal properties, marked by the transition from an ordered to a disordered structure.[64,66]

Retrogradation involves the reformation of double helices by amylopectin chains, resulting in the partial restoration of the crystalline structure.[76] The gelatinization and retrogradation temperatures of FB starch vary, being lower compared to other types of starch, due to the less compact packing of the B polymorphs.[68] Akintayo *et al.* (2022) emphasize that these processes are influenced by several factors, including genotype and location, as indicated by the studies. Due to the low organization of amylopectin crystallites, FB starch exhibits lower gelatinization and retrogradation enthalpies. Retrogradation, in general, manifests less distinctly compared to gelatinization, and its intensity increases after storage, influenced by amylose leaching and the amylose–amylopectin interaction.[66] It is observed that the retrogradation enthalpy (ΔH_r), which reflects the thermal energy involved in crystalline fusion and dissociation, along with the unraveling of the starch double helices, generally shows lower values than the gelatinization enthalpy.[68,76,77] The gelatinization enthalpy indicates the energy required for the starch to dissolve and form a paste when heated, while the retrogradation enthalpy refers to the energy needed for the starch to reorganize and form crystals upon cooling. For example, studies that stored FB paste starch at 4 °C for seven days recorded a lower retrogradation enthalpy (6.5 J g^{-1}) compared to the gelatinization enthalpy (12.4 J g^{-1}).[68,76,77]

It is noteworthy that lower retrogradation enthalpies suggest the starch tends to be more stable, with a lower tendency to harden, resulting in a more consistent texture during storage. FB starch, with its low gelatinization enthalpies, undergoes transformations during storage that can explain variations in gelatinization and retrogradation parameters. Although there are conflicting reports about its thermal stability, the ability of the swollen granules to maintain their integrity is a rheological advantage. Its potential is broad, encompassing strong gel food products, bioplastics, baking, and distillery applications, in addition to offering indirect benefits such as improved feed formulation and environmental preservation.[67] According to Ambigaipalan *et al.* (2011),[77] FB starch has a lower amylose leaching temperature range (70–75 °C) compared to other types of starch. However, due to the lower interaction between its components, amylose leaching is more extensive. This factor may influence the starch's paste temperature, causing FB starch to reach peak viscosity at relatively lower temperatures.[66] Ambigaipalan *et al.* (2011) suggest that this variation could be due to differences between cultivars or the presence of cracks in the starch granules. Regarding solubility, FB starch has the lowest solubility among legumes, possibly due to greater molecular integrity. All legumes showed an increase in solubility with rising temperature, indicating disorganization of the starch granules.

In conclusion, in terms of supply, cereals, roots, and tubers have traditionally been the main sources of starch, especially for industrial applications. However, due to the industry's pursuit of new functionalities, technological, and health benefits, there is growing interest in unconventional sources, such as legumes, which are now gaining recognition.[64,67] The fractionation of FB for the production of food ingredients has been generating increasing interest. However, the technological attributes of FB starch are still poorly understood. Its desirable functionality makes it suitable for various applications in the food industry, and starch modification can enhance its properties, further expanding its potential uses.[64]

7 Faba bean fibers

Dietary fibers are recognized by nutritionists as one of the most important essential nutrients, ranking seventh in terms of nutritional significance. They play a crucial role in promoting digestive health, aiding in the regulation of bowel movement, preventing diseases such as colon cancer and diverticulitis, and significantly contributing to blood sugar control, which is especially relevant for individuals with diabetes.[8,65,78] The ability of fibers to increase viscosity and retain components is related to their physical properties, while their fermentability in the colon depends on their chemical structure.[79] It is known that various processing methods can have either a positive or negative impact on the final fiber content in FB and other crops.[80] In addition to their role in the digestive tract, fibers are also widely recognized as thickeners, stabilizers, and emulsifiers, contributing to the texture and stability of various foods.[81,82] Notably, the average dietary fiber intake in most European countries generally does not meet the recommended levels.[78] Table 6 presents the main fibers present in FB, highlighting their respective amounts.

FB are widely recognized as an excellent source of dietary fiber, with low amounts of soluble fibers (0.6–1.1%) and higher amounts of insoluble fibers (10.7–16.0%).[2] Insoluble fibers contribute to the feeling of fullness and can help maintain a healthy weight, while soluble fibers are beneficial for controlling blood glucose levels, especially for individuals with diabetes or a predisposition to metabolic diseases.[7,83] It is emphasized that two distinct sources can be used in fiber extraction, namely the cotyledon and the hull.[62] The fiber content in whole FB varies considerably, typically ranging between 15% and 30%, with the main components being hemicellulose, cellulose, and lignin. To optimize the nutritional benefits, it is highly recommended to consume FB in their whole form. The dietary fiber present, for example, in the seed coat of FB plays a crucial role in digestive health, aiding in the regulation of intestinal transit and the prevention of gastrointestinal diseases. Therefore, incorporating the seed coat of FB into the daily diet not only increases fiber intake but also provides a range of additional health benefits, making FB a nutritionally valuable and versatile choice.[7,26,83]

The seed coat of FB, which is the outer layer of the seed, is widely recognized as an exceptionally rich source of dietary fiber, with a remarkable concentration of 82.3%.[83] This part of FB not only provides a high amount of fiber but also serves as a significant source of antioxidant phenolic compounds, *e.g.*, flavonoids and tannins, as well as essential minerals like iron, calcium, and potassium. The presence of these compounds gives the seed coat antioxidant and potentially anti-inflammatory properties, which are beneficial for human health.[7] In addition to playing a crucial role in intestinal health by modulating the microbiota—stimulating beneficial bacteria while inhibiting pathogens—fibers also possess properties such as water retention, viscosity, volume, fermentability, and bile acid binding. These characteristics directly influence gastrointestinal function and various physiological responses.[79,81,82] Gu *et al.*[80] observed that FB have a significantly higher dietary fiber content compared to lima bean, pinto bean, and red bean flours. This high fiber content in FB stands out not only for its quantity but also for its composition and the associated nutritional benefits.

Fibers have various applications, with gelation being one of the most notable. Gels formed by the combination of protein and fiber exhibit superior performance compared to those made solely with protein, indicating the continuous beneficial effect of fiber. This behavior aligns with the stable hydration properties of insoluble fibers, which are not affected by temperature.[84] The gels demonstrated promising results when replacing proteins with fibers, showing a reduction in fracture stress and strain, along with an increase in Young's modulus and storage modulus. In the mixtures studied by Johansson *et al.*,[62] the protein formed the continuous phase, while starch granules and fiber particles were homogeneously distributed within the gels, creating small cavities (<1 μm) where fiber and amylose aggregated. The addition of fiber and/or starch introduced heterogeneities in the protein matrix, which contributed to improved mechanical properties of the gel, such as reduced fracture stress and strain. Additionally, the water absorption capacity of fiber and starch granules increased protein concentration and moisture stability, reinforcing the overall gel structure. Johansson *et al.*[62] evaluated the gelation of protein extracted from FB at different pH values, as well as the impact of adding fibers derived from a byproduct of protein extraction, using cotyledon and hull as fiber sources. Gels produced at pH 4 and 5 exhibited reduced fracture stress and strain but displayed a higher Young's modulus compared to gels formed at pH 7.

Table 6 Studies evaluating the fibers of faba beans[a]

Product	TFC	SF	IF	NDF	ADF	Other information	References
Lyophilized fiber fraction	—	—	Lignin: 0.97 Cellulose: 14.20 Hemicellulose: 13.77	28.94	15.17	The partial substitution of proteins with fibers reduces fracture stress, increases the storage modulus, and preserves the protein network structure in the gels	62
Flour from the Estrela cultivar Fanfarra cultivar Banquete cultivar	16.59 14.11 12.19	0.62 1.06 0.55	15.96 13.05 11.64	—	—	There are variations in fiber content among faba cultivars. Soluble fiber helps reduce blood sugar levels, improves insulin response, and has beneficial effects on cancer, blood pressure, and inflammation. Insoluble fiber, on the other hand, increases fecal volume and accelerates gastrointestinal transit. The soluble and insoluble fiber fractions ranged from 0.55% to 1.06%, and from 10.70% to 15.96%, respectively	2
Flour	13.80	4.74	9.07	—	—	Faba flour exhibited a significantly higher total dietary fiber content compared to wheat flour, due to its higher insoluble fiber content. While soluble fiber easily dissolves in water, forming viscous solutions, insoluble fiber is not soluble and reaches the large intestine undigested	88
Raw flour Soaked flour Germinated flour (24 h) (48 h)	17.4 18.3 16.9 18.8	—	—	—	—	Faba flour exhibited a higher total dietary fiber content than yellow pea flour, reaching 17.4% in its raw form. Insoluble fiber was predominant and remained relatively stable during germination. The soaking and germination process affected the structure of the protein and fiber matrix, making the starch more accessible to digestion. Additionally, fiber plays an important role in the viscosity and functionality of the flours, influencing the technological and nutritional properties of the final products	63

[a] TFC = total fiber content; SF = soluble fibers; IF = insoluble fibers; NDF = neutral detergent fiber; ADF = acid detergent fiber.

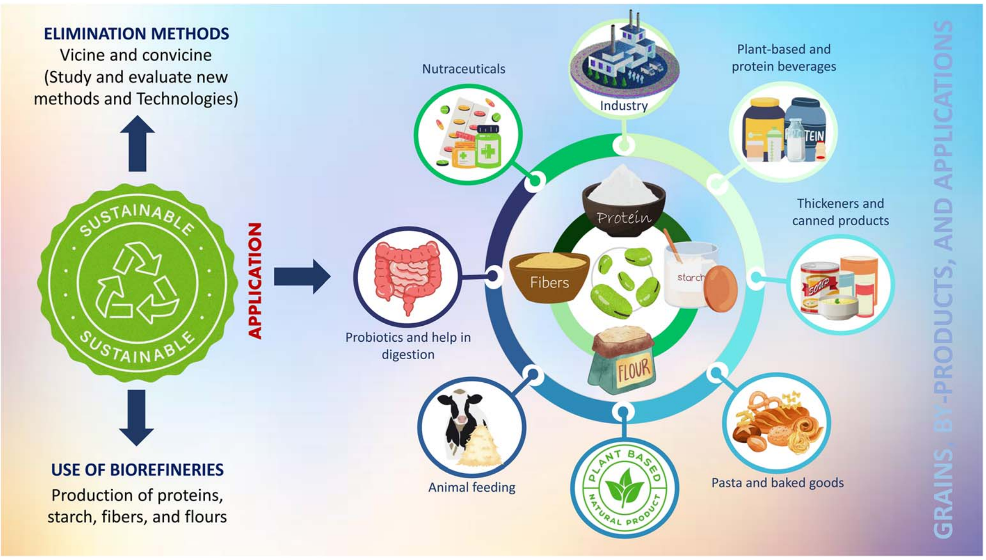

Fig. 5 Proposed applications of the faba bean biorefinery concept for mitigating antinutritional factors and enabling new industrial applications.

The addition of fiber, regardless of its origin (cotyledon or hull), significantly influenced the textural properties of the gels. Microscopic analyses revealed aggregated microstructures in the pH 4 and 5 gels, whereas the pH 7 gels displayed a fine-stranded protein network. Furthermore, low-field nuclear magnetic resonance (LF-NMR) highlighted differences in water mobility among the gels, attributed to variations in microstructure and the water-binding properties of the fibers.

Prebiotics are considered a promising and safe approach to addressing various health-related challenges, although further research is needed to optimize food systems that maximize their functional properties. The insoluble dietary fiber found in legumes, such as FB, has been associated with prebiotic effects, along with antioxidant, anti-inflammatory, and anticancer activities.[85] Additionally, bioactive peptides derived from FB have demonstrated significant ABTS and DPPH radical-scavenging capacity, as well as ferrous ion-chelating potential.[86] It is important to highlight that fiber consists of carbohydrate polymers with more than ten monomeric units that are not digested by endogenous enzymes in the human small intestine. In FB, its presence contributes to glycemic regulation, cholesterol reduction, and intestinal health promotion.[87]

8 Future trends

The future of FB utilization is strongly tied to advancements in food technology, biotechnology, and sustainable agriculture. Some emerging trends include (Fig. 5):

Improved processing techniques: novel technologies such as enzymatic hydrolysis, fermentation, and physical treatments (*e.g.*, pulsed electric fields, ultrasonication) will enhance the digestibility, functional properties, and sensory characteristics of FB-based ingredients.

Plant-based innovations: the growing demand for alternative proteins in dairy and meat analogs will drive research into optimizing FB protein functionality, improving solubility, and reducing off-flavors.

Prebiotic and functional foods: the development of prebiotic-rich FB products, including fiber-enriched formulations, could support gut health and expand their use in functional food markets.

Circular economy applications: integration of FB biorefineries into sustainable food production chains will contribute to waste reduction and valorization of agricultural byproducts.

Genetic and breeding advances: genetic modifications and breeding programs targeting low-antinutrient FB varieties will facilitate broader adoption in the food industry.

FB play a crucial role in fostering more sustainable and resilient food systems. Their ability to enhance soil fertility, reduce dependence on finite natural resources, and provide balanced diets makes them a valuable component in addressing global agricultural and food security challenges. Moreover, promoting the consumption of FB not only contributes to public health by offering a nutrient-dense alternative to conventional protein sources but also drives a positive transition toward a more sustainable food future. Investing in the cultivation, consumption, and research of FB is essential to unlocking their full nutritional and functional potential. However, addressing the presence of antinutritional compounds such as vicine and convicine is crucial to improving their digestibility and bioavailability. Advancements in food processing technologies, including fermentation, enzymatic treatments, and novel extraction methods, are necessary to optimize the utilization of FB in diverse food applications.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Conflict of interest and authorship conformation form. All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version.

Abbreviations

3D:	Three-dimensional
AA:	Amino acid
ABTS:	Ácido 2,2′-azinobis(3-etilbenzotiazolina-6-s)
ADF:	Acid detergent fiber
AML:	Amylose
AMP:	Amylopectin
BD:	Breakdown
CAGR:	Compound annual growth rate
D:	Digestibility
DP:	Degree of polymerization
DPPH:	2,2-Difenil-1-picrilhidrazil
e.g.:	Exempli gratia
EP:	Expansion power
FB:	Faba beans
FFC:	Foam formation capacity
FS:	Foam stability
FV:	Final viscosity
G:	Gelatinization
G6PD:	Glucose-6-phosphate dehydrogenase
GC:	Crystallinity degree
GT:	Pasting temperature
IBGE:	Brazilian institute of geography and statistics
IF:	Insoluble fibers
L-DOPA:	Levodopa
LF-NMR:	Low-field nuclear magnetic resonance
LT:	Light transmittance
mg per g DM:	Milligrams per gram of dry matter
MS:	Modified starch
NDF:	Neutral detergent fiber
OBC:	Oil-binding capacity
PP:	Pasting properties
PS:	Protein solubility
PT:	Peak time
PV:	Peak viscosity
R$:	Brazilian real (BRL)
RDS:	Rapidly digestible starch
RS:	Resistant starch
RS:	Resistant starch
RSF:	Retrograded starch fusion
S:	Solubility
SB:	Setback
SDGs:	Sustainable development goals
SDS:	Slowly digestible starch
SF:	Soluble fibers
T_c:	Conclusion temperature
TFC:	Total fiber content
T_o:	Onset temperature
T_p:	Peak temperature
TV:	Trough viscosity
USD:	United States Dollar
WHC:	Water-holding capacity
ΔH:	Gelatinization enthalpy
ΔH_r:	Retrogradation enthalpy
ΔT_r:	Gelatinization temperature range

Data availability

No new data were generated or analyzed in support of this study.

Acknowledgements

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001, and by the Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG) for financial support (APQ-05316-23; APQ-03368-24; APD-01570-25). Dr Paulo César Stringheta and Dr Pedro Henrique Campelo thank the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for their research scholarships (310859/2025-5 and 309014/2025-5, respectively). Dr Thais Caroline Buttow Rigolon thanks CAPES for her scholarship (88887.106105/2025-00).

References

1 C. G. Athanassiou, S. Smetana, D. Pleissner, A. Tassoni, L. Gasco, F. Gai, A. Shpigelman, M. Bravo Cadena, M. Gastli, L. E. C. Conceição, E. Gronich, S. Paolacci, V. Chalkidis, M. Kuthy, R. E. Stolzenberger, A. El Yaacoubi, C. Mehlhose, J.-I. Petrusán and C. I. Rumbos, Circular and Inclusive Utilization of Alternative Proteins: A European and Mediterranean Perspective, *Curr. Opin. Green Sustainable Chem.*, 2024, **46**, 100892, DOI: 10.1016/j.cogsc.2024.100892.

2 I.-C. Mayer Labba, H. Frøkiær and A.-S. Sandberg, Nutritional and Antinutritional Composition of Fava Bean (*Vicia Faba* L., Var. Minor) Cultivars, *Food Res. Int.*, 2021, **140**, 110038, DOI: 10.1016/j.foodres.2020.110038.

3 G. Dragone, A. A. J. Kerssemakers, J. L. S. P. Driessen, C. K. Yamakawa, L. P. Brumano and S. I. Mussatto, Innovation and Strategic Orientations for the Development of Advanced Biorefineries, *Bioresour. Technol.*, 2020, **302**, 122847, DOI: 10.1016/j.biortech.2020.122847.

4 *Faba Bean: Chemistry, Properties and Functionality*, ed. S. Punia Bangar and S. Bala Dhull, Springer International Publishing, Cham, 2022, DOI: 10.1007/978-3-031-14587-2.

5 J. King, S. Y. Leong, M. Alpos, C. Johnson, S. McLeod, M. Peng, K. Sutton and I. Oey, Role of Food Processing and Incorporating Legumes in Food Products to Increase Protein Intake and Enhance Satiety, *Trends Food Sci. Technol.*, 2024, **147**, 104466, DOI: 10.1016/j.tifs.2024.104466.

6 M. A. Augustin and M. B. Cole, Towards a Sustainable Food System by Design Using Faba Bean Protein as an Example, *Trends Food Sci. Technol.*, 2022, **125**, 1–11, DOI: 10.1016/j.tifs.2022.04.029.

7 V. Chaudhary, P. Kajla and Shobhit, Chemistry, Nutrient Composition and Quality of Faba Beans, in *Faba Bean: Chemistry, Properties and Functionality*, ed. S. Punia Bangar, S. Bala Dhull, Springer International Publishing, Cham, 2022, pp. 75–96, DOI: 10.1007/978-3-031-14587-2_4.
8 I. M. Valente, A. R. J. Cabrita, N. Malushi, H. M. Oliveira, L. Papa, J. A. Rodrigues, A. J. M. Fonseca and M. R. G. Maia, Unravelling the Phytonutrients and Antioxidant Properties of European *Vicia Faba* L. Seeds, *Food Res. Int.*, 2019, **116**, 888–896, DOI: 10.1016/j.foodres.2018.09.025.
9 R. D. Semba, R. Ramsing, N. Rahman, K. Kraemer and M. W. Bloem, Legumes as a Sustainable Source of Protein in Human Diets, *Global Food Secur.*, 2021, **28**, 100520, DOI: 10.1016/j.gfs.2021.100520.
10 D. Martineau-Côté, L. L'Hocine, F. Tuccillo, J. P. D. Wanasundara and F. L. Stoddard, Faba Bean as a Sustainable Plant Protein Source, in *Sustainable Protein Sources*, ed. S. Nadathur, J. P. D. Wanasundara and L. Scanlin, Academic Press, 2nd edn, 2024, ch. 8, pp. 163–184, DOI: 10.1016/B978-0-323-91652-3.00001-0.
11 E. Ivarsson and M. Neil, Variations in Nutritional and Antinutritional Contents among Faba Bean Cultivars and Effects on Growth Performance of Weaner Pigs, *Livest. Sci.*, 2018, **212**, 14–21, DOI: 10.1016/j.livsci.2018.03.017.
12 H. Khazaei, R. W. Purves, J. Hughes, W. Link, D. M. O'Sullivan, A. H. Schulman, E. Björnsdotter, F. Geu-Flores, M. Nadzieja, S. U. Andersen, J. Stougaard, A. Vandenberg and F. L. Stoddard, Eliminating Vicine and Convicine, the Main Anti-Nutritional Factors Restricting Faba Bean Usage, *Trends Food Sci. Technol.*, 2019, **91**, 549–556, DOI: 10.1016/j.tifs.2019.07.051.
13 I. Leinonen, P. P. M. Iannetta, M. MacLeod, R. M. Rees, W. Russell, C. Watson and A. P. Barnes, Regional Land Use Efficiency and Nutritional Quality of Protein Production, *Global Food Secur.*, 2020, **26**, 100386, DOI: 10.1016/j.gfs.2020.100386.
14 UN, *U. N. Sustainable Development Goals Knowledge Platform*, 2015.
15 S. Corrado, C. Caldeira, M. Eriksson, O. J. Hanssen, H.-E. Hauser, F. Van Holsteijn, G. Liu, K. Östergren, A. Parry, L. Secondi, Å. Stenmarck and S. Sala, Food Waste Accounting Methodologies: Challenges, Opportunities, and Further Advancements, *Global Food Secur.*, 2019, **20**, 93–100, DOI: 10.1016/j.gfs.2019.01.002.
16 M. Rivers, M. Hinge, K. Rassool, S. Blouin, F. U. Jehn, J. B. G. Martínez, V. A. Grilo, V. Jaeck, R. J. Tieman, J. Mulhall, T. E. Butt and D. C. Denkenberger, Food System Adaptation and Maintaining Trade Could Mitigate Global Famine in Abrupt Sunlight Reduction Scenarios, *Global Food Secur.*, 2024, **43**, 100807, DOI: 10.1016/j.gfs.2024.100807.
17 C. Li and M. Umair, Does Green Finance Development Goals Affects Renewable Energy in China, *Renewable Energy*, 2023, **203**, 898–905, DOI: 10.1016/j.renene.2022.12.066.
18 X. Yang and L. Long, Renewable Energy Transition and Its Implication on Natural Resource Management for Green and Sustainable Economic Recovery, *Resour. Policy*, 2024, **89**, 104624, DOI: 10.1016/j.resourpol.2023.104624.
19 L. Lange and A. S. Meyer, Potentials and Possible Safety Issues of Using Biorefinery Products in Food Value Chains, *Trends Food Sci. Technol.*, 2019, **84**, 7–11, DOI: 10.1016/j.tifs.2018.08.016.
20 A. T. Ubando, C. B. Felix and W.-H. Chen, Biorefineries in Circular Bioeconomy: A Comprehensive Review, *Bioresour. Technol.*, 2020, **299**, 122585, DOI: 10.1016/j.biortech.2019.122585.
21 H. Karlsson, S. Ahlgren, I. Strid and P.-A. Hansson, Faba Beans for Biorefinery Feedstock or Feed? Greenhouse Gas and Energy Balances of Different Applications, *Agric. Syst.*, 2015, **141**, 138–148, DOI: 10.1016/j.agsy.2015.10.004.
22 V. Caracuta, J. Vardi, Y. Paz and E. Boaretto, Farming Legumes in the Pre-Pottery Neolithic: New Discoveries from the Site of Ahihud (Israel), *PLoS One*, 2017, **12**(5), e0177859, DOI: 10.1371/journal.pone.0177859.
23 A. Karkanis, G. Ntatsi, L. Lepse, J. A. Fernández, I. M. Vågen, B. Rewald, I. Alsiņa, A. Kronberga, A. Balliu, M. Olle, G. Bodner, L. Dubova, E. Rosa and D. Savvas, Faba Bean Cultivation – Revealing Novel Managing Practices for More Sustainable and Competitive European Cropping Systems, *Front. Plant Sci.*, 2018, **9**, 1115, DOI: 10.3389/fpls.2018.01115.
24 F. Maalouf, S. Ahmed and Z. Bishaw, Faba Bean, in *The Beans and the Peas*, ed. A. Pratap and S. Gupta, Woodhead Publishing, 2021, ch. 6, pp. 105–131, DOI: 10.1016/B978-0-12-821450-3.00008-1.
25 H. Khazaei, D. M. O'Sullivan, F. L. Stoddard, K. N. Adhikari, J. G. Paull, A. H. Schulman, S. U. Andersen and A. Vandenberg, Recent Advances in Faba Bean Genetic and Genomic Tools for Crop Improvement, *Legume Sci.*, 2021, **3**(3), e75, DOI: 10.1002/leg3.75.
26 K. Crépon, P. Marget, C. Peyronnet, B. Carrouée, P. Arese and G. Duc, Nutritional Value of Faba Bean (*Vicia Faba* L.) Seeds for Feed and Food, *Field Crops Res.*, 2010, **115**(3), 329–339, DOI: 10.1016/j.fcr.2009.09.016.
27 F. Etemadi, M. Hashemi, A. V. Barker, O. R. Zandvakili and X. Liu, Agronomy, Nutritional Value, and Medicinal Application of Faba Bean (*Vicia Faba* L.), *Hortic. Plant J.*, 2019, **5**(4), 170–182, DOI: 10.1016/j.hpj.2019.04.004.
28 Mundial Report. Relatório de Mercado Global Da Faba Beans 2023, 2023. https://www.researchandmarkets.com/r/aybsf6 (accessed 2025-03-20).
29 J. Mexe, *A Cultura Da Fava: Técnicas Culturais*, 2022.
30 E. S. Jensen, M. B. Peoples and H. Hauggaard-Nielsen, Faba Bean in Cropping Systems, *Field Crops Res.*, 2010, **115**(3), 203–216, DOI: 10.1016/j.fcr.2009.10.008.
31 BusinessWire, Relatório de Mercado Global Da Faba Beans 2021, 2021. https://www.businesswire.com/news/home/20211213005626/en/Faba-Beans-Global-Market-Report-2021-Featuring-Prairie-Fava-Unigrain-Roland-Beans-Aviip-Group-Alberta-Pulse-Growers-Stamp-Seeds-Riddell-Seed-and-Pawnee-Buttes-Seed—ResearchAndMarkets.com (accessed 2025-03-20).
32 Mundial Report. Relatório de Mercado Global Da Faba Beans 2024, 2024. https://www.researchandmarkets.com/report/fava-bean#rela0-5744237. (accessed 2025-03-20).

33 IBGE, I. B. de G. e E. Produção de Fava, 2022. https://www.ibge.gov.br/explica/producao-agropecuaria/fava/br (accessed 2023-04-23).

34 IBGE, I. B. de G. e E. Produção de Fava, 2023. https://www.ibge.gov.br/explica/producao-agropecuaria/fava/br (accessed 2024-11-24).

35 F. Boukid and M. Castellari, How Can Processing Technologies Boost the Application of Faba Bean (*Vicia Faba* L.) Proteins in Food Production?, *eFood*, 2022, **3**(3), e18, DOI: 10.1002/efd2.18.

36 S. Mesfin, G. Gebresamuel, M. Haile, A. Zenebe and G. Desta, Mineral Fertilizer Demand for Optimum Biological Nitrogen Fixation and Yield Potentials of Legumes in Northern Ethiopia, *Sustainability*, 2020, **12**(16), 6449, DOI: 10.3390/su12166449.

37 F. Palmero, J. A. Fernandez, F. O. Garcia, R. J. Haro, P. V. V. Prasad, F. Salvagiotti and I. A. Ciampitti, A Quantitative Review into the Contributions of Biological Nitrogen Fixation to Agricultural Systems by Grain Legumes, *Eur. J. Agron.*, 2022, **136**, 126514, DOI: 10.1016/j.eja.2022.126514.

38 K. Schulz-Kesting, J. Thiele, G. Everwand and J. Dauber, Neighbourhood Effect of Faba Bean (*Vicia Faba* L.) on Density of Vegetation-Dwelling Natural Biocontrol Agents in Winter Wheat, *Biol. Control*, 2021, **160**, 104673, DOI: 10.1016/j.biocontrol.2021.104673.

39 C. Johnston, S. Y. Leong, C. Teape, V. Liesaputra and I. Oey, 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 Chem.*, 2024, **449**, 139321, DOI: 10.1016/j.foodchem.2024.139321.

40 X. Cao, J. Luo, X. Wang, Z. Chen, G. Liu, M. B. Khan, K. J. Kang, Y. Feng, Z. He and X. Yang, Responses of Soil Bacterial Community and Cd Phytoextraction to a *Sedum Alfredii*-Oilseed Rape (*Brassica Napus* L. and *Brassica Juncea* L.) Intercropping System, *Sci. Total Environ.*, 2020, **723**, 138152, DOI: 10.1016/j.scitotenv.2020.138152.

41 M. Marcos-Pérez, V. Sánchez-Navarro and R. Zornoza, Intercropping Systems between Broccoli and Fava Bean Can Enhance Overall Crop Production and Improve Soil Fertility, *Sci. Hortic.*, 2023, **312**, 111834, DOI: 10.1016/j.scienta.2023.111834.

42 F. d. O. Pereira, I. R. Martins, S. d. C. A. Ribeiro, J. C. Suzuki and M. R. S. P. Joele, Métodos para redução e inativação de fatores antinutricionais em alimentos de origem vegetal: uma revisão, *Nutr. Rev. Nutr. E Vigilância Em Saúde*, 2023, **10**(1), E11010, DOI: 10.59171/nutrivisa-2023v10e11010.

43 M. Pulkkinen, M. Gautam, A.-M. Lampi, V. Ollilainen, F. Stoddard, T. Sontag-Strohm, H. Salovaara and V. Piironen, Determination of Vicine and Convicine from Faba Bean with an Optimized High-Performance Liquid Chromatographic Method, *Food Res. Int.*, 2015, **76**, 168–177, DOI: 10.1016/j.foodres.2015.05.031.

44 A. Badjona, R. Bradshaw, C. Millman, M. Howarth and B. Dubey, Structural, Thermal, and Physicochemical Properties of Ultrasound-Assisted Extraction of Faba Bean Protein Isolate (FPI), *J. Food Eng.*, 2024, **377**, 112082, DOI: 10.1016/j.jfoodeng.2024.112082.

45 M. Krause, J. C. Sørensen, I. L. Petersen, P. Duque-Estrada, C. Cappello, A. Z. A. Tlais, R. Di Cagno, L. Ispiryan, A. W. Sahin, E. K. Arendt and E. Zannini, Associating Compositional, Nutritional and Techno-Functional Characteristics of Faba Bean (Vicia Faba L.) Protein Isolates and Their Production Side-Streams with Potential Food Applications, *Foods*, 2023, **12**(5), 919, DOI: 10.3390/foods12050919.

46 K. K. Ma, M. Greis, J. Lu, A. A. Nolden, D. J. McClements and A. J. Kinchla, Functional Performance of Plant Proteins, *Foods*, 2022, **11**(4), 594, DOI: 10.3390/foods11040594.

47 D. Żmudziński, U. Goik and P. Ptaszek, Functional and Rheological Properties of Vicia Faba L. Protein Isolates, *Biomolecules*, 2021, **11**(2), 178, DOI: 10.3390/biom11020178.

48 J. Lu, G. Zamaratskaia, M. Langton, H. E. Röhnisch and S. Karkehabadi, Minimizing Anti-Nutritional Factors in Wet Protein Extraction from Swedish Faba Beans through the Application of Response Surface Methodology, *Food Chem.*, 2024, **460**, 140700, DOI: 10.1016/j.foodchem.2024.140700.

49 F. Tuccillo, K. Kantanen, Y. Wang, J. Martin Ramos Diaz, M. Pulkkinen, M. Edelmann, A. Knaapila, K. Jouppila, V. Piironen, A.-M. Lampi, M. Sandell and K. Katina, The Flavor of Faba Bean Ingredients and Extrudates: Chemical and Sensory Properties, *Food Res. Int.*, 2022, **162**, 112036, DOI: 10.1016/j.foodres.2022.112036.

50 S. B. Dhull, M. K. Kidwai, R. Noor, P. Chawla and P. K. Rose, A Review of Nutritional Profile and Processing of Faba Bean (Vicia Faba L.), *Legume Sci.*, 2022, **4**(3), e129, DOI: 10.1002/leg3.129.

51 J. Thomsen, J. Rao and B. Chen, Faba Bean Protein: Chemical Composition, Functionality, Volatile Compounds, and Applications in Food Production, *Trends Food Sci. Technol.*, 2025, **156**, 104863, DOI: 10.1016/j.tifs.2024.104863.

52 S. O. Keskin, T. M. Ali, J. Ahmed, M. Shaikh, M. Siddiq and M. A. Uebersax, Physico-chemical and Functional Properties of Legume Protein, Starch, and Dietary Fiber—A Review, *Legume Sci.*, 2022, **4**(1), e117, DOI: 10.1002/leg3.117.

53 I. C. Ohanenye, F.-G. C. Ekezie, R. A. Sarteshnizi, R. T. Boachie, C. U. Emenike, X. Sun, I. D. Nwachukwu and C. C. Udenigwe, Legume Seed Protein Digestibility as Influenced by Traditional and Emerging Physical Processing Technologies, *Foods*, 2022, **11**(15), 2299, DOI: 10.3390/foods11152299.

54 T. D. Oluwajuyitan and R. E. Aluko, Structural and Functional Properties of Fava Bean Albumin, Globulin and Glutelin Protein Fractions, *Food Chem.: X*, 2025, **25**, 102104, DOI: 10.1016/j.fochx.2024.102104.

55 A. O. Warsame, N. Michael, D. M. O'Sullivan and P. Tosi, Identification and Quantification of Major Faba Bean Seed Proteins, *J. Agric. Food Chem.*, 2020, **68**(32), 8535–8544, DOI: 10.1021/acs.jafc.0c02927.

56 S. Gulzar, O. Martín-Belloso and R. Soliva-Fortuny, Tailoring the Techno-Functional Properties of Fava Bean Protein

Isolates: A Comparative Evaluation of Ultrasonication and Pulsed Electric Field Treatments, *Foods*, 2024, **13**(3), 376, DOI: 10.3390/foods13030376.

57 I. Berrazaga, J. L. Mession, K. Laleg, J. Salles, C. Guillet, V. Patrac, C. Giraudet, O. Le Bacquer, Y. Boirie, V. Micard, F. Husson, R. Saurel and S. Walrand, Formulation, Process Conditions, and Biological Evaluation of Dairy Mixed Gels Containing Fava Bean and Milk Proteins: Effect on Protein Retention in Growing Young Rats, *J. Dairy Sci.*, 2019, **102**(2), 1066–1082, DOI: 10.3168/jds.2018-14610.

58 L. Day, Proteins from Land Plants – Potential Resources for Human Nutrition and Food Security, *Trends Food Sci. Technol.*, 2013, **32**(1), 25–42, DOI: 10.1016/j.tifs.2013.05.005.

59 A. Martínez-Velasco, C. Lobato-Calleros, B. E. Hernández-Rodríguez, A. Román-Guerrero, J. Alvarez-Ramirez and E. J. Vernon-Carter, High Intensity Ultrasound Treatment of Faba Bean (*Vicia Faba* L.) Protein: Effect on Surface Properties, Foaming Ability and Structural Changes, *Ultrason. Sonochem.*, 2018, **44**, 97–105, DOI: 10.1016/j.ultsonch.2018.02.007.

60 J.-L. Mession, M. L. Chihi, N. Sok and R. Saurel, Effect of Globular Pea Proteins Fractionation on Their Heat-Induced Aggregation and Acid Cold-Set Gelation, *Food Hydrocoll.*, 2015, **46**, 233–243, DOI: 10.1016/j.foodhyd.2014.11.025.

61 K. Shevkani, N. Singh, A. Kaur and J. C. Rana, Structural and Functional Characterization of Kidney Bean and Field Pea Protein Isolates: A Comparative Study, *Food Hydrocoll.*, 2015, **43**, 679–689, DOI: 10.1016/j.foodhyd.2014.07.024.

62 M. Johansson, D. Johansson, A. Ström, J. Rydén, K. Nilsson, J. Karlsson, R. Moriana and M. Langton, Effect of Starch and Fibre on Faba Bean Protein Gel Characteristics, *Food Hydrocoll.*, 2022, **131**, 107741, DOI: 10.1016/j.foodhyd.2022.107741.

63 R. Setia, Z. Dai, M. T. Nickerson, E. Sopiwnyk, L. Malcolmson and Y. Ai, Impacts of Short-Term Germination on the Chemical Compositions, Technological Characteristics and Nutritional Quality of Yellow Pea and Faba Bean Flours, *Food Res. Int.*, 2019, **122**, 263–272, DOI: 10.1016/j.foodres.2019.04.021.

64 S. Punia, S. B. Dhull, K. S. Sandhu and M. Kaur, Faba Bean (Vicia Faba) Starch: Structure, Properties, and in Vitro Digestibility—A Review, *Legume Sci.*, 2019, **1**(1), e18, DOI: 10.1002/leg3.18.

65 S. Vishnupriya, D. Roshini, S. Bhavaniramya, Karthiayani and V. Ramar, Faba Bean Starch: Structure, Functionality, and Applications, in *Non-Conventional Starch Sources*, Elsevier, 2024, pp. 409–438, DOI: 10.1016/B978-0-443-18981-4.00014-8.

66 O. A. Akintayo, S. J. Zhou, O. R. Karim, T. Grassby and S. A. Oyeyinka, Faba Bean Starch: Structure, Physicochemical Properties, Modification, and Potential Industrial Applications, in *Faba Bean: Chemistry, Properties and Functionality*, ed. S. Punia Bangar and S. Bala Dhull, Springer International Publishing, Cham, 2022, pp. 211–243, DOI: 10.1007/978-3-031-14587-2_9.

67 S. A. Oyeyinka, E. Kayitesi, O. A. Adebo, A. B. Oyedeji, O. M. Ogundele, A. O. Obilana and P. B. Njobeh, A Review on the Physicochemical Properties and Potential Food Applications of Cowpea (Vigna Unguiculata) Starch, *Int. J. Food Sci. Technol.*, 2021, **56**(1), 52–60, DOI: 10.1111/ijfs.14604.

68 L. Li, T. Z. Yuan, R. Setia, R. B. Raja, B. Zhang and Y. Ai, Characteristics of Pea, Lentil and Faba Bean Starches Isolated from Air-Classified Flours in Comparison with Commercial Starches, *Food Chem.*, 2019, **276**, 599–607, DOI: 10.1016/j.foodchem.2018.10.064.

69 B. A. Sofi, I. A. Wani, F. A. Masoodi, I. Saba and S. Muzaffar, Effect of Gamma Irradiation on Physicochemical Properties of Broad Bean (*Vicia Faba* L.) Starch, *LWT-Food Sci. Technol.*, 2013, **54**(1), 63–72, DOI: 10.1016/j.lwt.2013.05.021.

70 R. Hoover, T. Hughes, H. J. Chung and Q. Liu, Composition, Molecular Structure, Properties, and Modification of Pulse Starches: A Review, *Food Res. Int.*, 2010, **43**(2), 399–413, DOI: 10.1016/j.foodres.2009.09.001.

71 Z. Zhang, X. Tian, P. Wang, H. Jiang and W. Li, Compositional, Morphological, and Physicochemical Properties of Starches from Red Adzuki Bean, Chickpea, Faba Bean, and Baiyue Bean Grown in China, *Food Sci. Nutr.*, 2019, **7**(8), 2485–2494, DOI: 10.1002/fsn3.865.

72 N. Moussou, M. Ouazib, J. Wanasundara, F. Zaidi and L. A. Rubio, Nutrients and Non-Nutrients Composition and in Vitro Starch Digestibility of Five Algerian Legume Seed Flours, *Int. Food Res. J.*, 2019, **6**(4), 1339–1349.

73 M. P. Gangola, B. R. Ramadoss, S. Jaiswal, C. Chan, R. Mollard, H. Fabek, M. Tulbek, P. Jones, D. Sanchez-Hernandez, G. H. Anderson and R. N. Chibbar, Faba Bean Meal, Starch or Protein Fortification of Durum Wheat Pasta Differentially Influence Noodle Composition, Starch Structure and *in Vitro* Digestibility, *Food Chem.*, 2021, **349**, 129167, DOI: 10.1016/j.foodchem.2021.129167.

74 T. Suárez-Diéguez, F. Pérez-Moreno, J. A. Ariza-Ortega, G. López-Rodríguez and J. A. Nieto, Obtention and Characterization of Resistant Starch from Creole Faba Bean (*Vicia Faba L.* Creole) as a Promising Functional Ingredient, *LWT*, 2021, **145**, 111247, DOI: 10.1016/j.lwt.2021.111247.

75 L. A. Bello-Pérez, J. J. Islas-Hernández, J. R. Rendón-Villalobos, E. Agama-Acevedo, L. Morales-Franco and J. Tovar, *In Vitro* Starch Digestibility of Fresh and Sun-dried Faba Beans (*Vicia Faba* L.), *J. Sci. Food Agric.*, 2007, **87**(8), 1517–1522, DOI: 10.1002/jsfa.2876.

76 P. Ambigaipalan, R. Hoover, E. Donner and Q. Liu, Retrogradation Characteristics of Pulse Starches, *Food Res. Int.*, 2013, **54**(1), 203–212, DOI: 10.1016/j.foodres.2013.06.012.

77 P. Ambigaipalan, R. Hoover, E. Donner, Q. Liu, S. Jaiswal, R. Chibbar, K. K. M. Nantanga and K. Seetharaman, Structure of Faba Bean, Black Bean and Pinto Bean Starches at Different Levels of Granule Organization and Their Physicochemical Properties, *Food Res. Int.*, 2011, **44**(9), 2962–2974, DOI: 10.1016/j.foodres.2011.07.006.

78 A. M. Stephen, M. M.-J. Champ, S. J. Cloran, M. Fleith, L. Van Lieshout, H. Mejborn and V. J. Burley, Dietary Fibre in Europe: Current State of Knowledge on Definitions,

Sources, Recommendations, Intakes and Relationships to Health, *Nutr. Res. Rev.*, 2017, **30**(2), 149–190, DOI: 10.1017/S095442241700004X.

79 S. M. Tosh and S. Yada, Dietary Fibres in Pulse Seeds and Fractions: Characterization, Functional Attributes, and Applications, *Food Res. Int.*, 2010, **43**(2), 450–460, DOI: 10.1016/j.foodres.2009.09.005.

80 B.-J. Gu, M. D. P. Masli and G. M. Ganjyal, Whole Faba Bean Flour Exhibits Unique Expansion Characteristics Relative to the Whole Flours of Lima, Pinto, and Red Kidney Beans during Extrusion, *J. Food Sci.*, 2020, **85**(2), 404–413, DOI: 10.1111/1750-3841.14951.

81 T. Liu, X. Zhen, H. Lei, J. Li, Y. Wang, D. Gou and J. Zhao, Investigating the Physicochemical Characteristics and Importance of Insoluble Dietary Fiber Extracted from Legumes: An in-Depth Study on Its Biological Functions, *Food Chem.: X*, 2024, **22**, 101424, DOI: 10.1016/j.fochx.2024.101424.

82 S. Muñoz-Pina, K. Khvostenko, J. García-Hernández, A. Heredia and A. Andrés, *In Vitro* Digestibility and Angiotensin Converting Enzyme (ACE) Inhibitory Activity of Solid-State Fermented Fava Beans (*Vicia Faba* L.), *Food Chem.*, 2024, **455**, 139867, DOI: 10.1016/j.foodchem.2024.139867.

83 S. Çalışkantürk Karataş, D. Günay and S. Sayar, In Vitro Evaluation of Whole Faba Bean and Its Seed Coat as a Potential Source of Functional Food Components, *Food Chem.*, 2017, **230**, 182–188, DOI: 10.1016/j.foodchem.2017.03.037.

84 X. Zhuang, L. Wang, X. Jiang, Y. Chen and G. Zhou, The Effects of Three Polysaccharides on the Gelation Properties of Myofibrillar Protein: Phase Behaviour and Moisture Stability, *Meat Sci.*, 2020, **170**, 108228, DOI: 10.1016/j.meatsci.2020.108228.

85 F. Admasu, E. G. Fentie, H. Admassu and J.-H. Shin, Functionalization of Wheat Bread with Prebiotic Dietary Insoluble Fiber from Orange-Fleshed Sweet Potato Peel and Haricot Bean Flours, *LWT*, 2024, **200**, 116182, DOI: 10.1016/j.lwt.2024.116182.

86 S. P. Samaei, M. Ghorbani, D. Tagliazucchi, S. Martini, R. Gotti, T. Themelis, F. Tesini, A. Gianotti, T. Gallina Toschi and E. Babini, Functional, Nutritional, Antioxidant, Sensory Properties and Comparative Peptidomic Profile of Faba Bean (*Vicia Faba*, L.) Seed Protein Hydrolysates and Fortified Apple Juice, *Food Chem.*, 2020, **330**, 127120, DOI: 10.1016/j.foodchem.2020.127120.

87 Z. Feng, J. D. Morton, E. Maes, L. Kumar and L. Serventi, Exploring Faba Beans (*Vicia Faba* L.): Bioactive Compounds, Cardiovascular Health, and Processing Insights, *Crit. Rev. Food Sci. Nutr.*, 2024, 1–14, DOI: 10.1080/10408398.2024.2387330.

88 K. A. Millar, E. Gallagher, R. Burke, S. McCarthy and C. Barry-Ryan, Proximate Composition and Anti-Nutritional Factors of Fava-Bean (*Vicia Faba*), Green-Pea and Yellow-Pea (*Pisum Sativum*) Flour, *J. Food Compos. Anal.*, 2019, **82**, 103233, DOI: 10.1016/j.jfca.2019.103233.

