Plant protein ingredients

Between techno-functionality, sensory properties, human nutrition and sustainability

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Abstract

Research on plant-based proteins is still in its early stages. The effects of manufacturing processes on their chemical composition (nutritive and potentially 'anti-nutritive' components), on their techno-functional and on their sensory properties are not yet fully understood. Additionally, the influence of different processing levels on the nutritional quality remains unclear, as does the question of whether plant proteins are truly more sustainable than conventional animal proteins. Within the NewFoodSystems Innovation Space, three projects aim to shed light on these questions: 'Sustainable protein ingredients', 'AlProPlant' and 'Pr:Ins – Holistic assessment'. Findings of these projects are presented in this article.

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Introduction

Ensuring a sustainable supply of high-quality food for the world's growing population requires a significant increase in food production. As competition for available arable land continues to intensify, new land-saving production concepts are needed. Given the high resources and land consumption associated with animal product production, alternative protein sources are increasingly being explored. Plant proteins could serve as one such alternative [1], provided they are at least comparable, if not superior, to animal proteins in terms of techno-functional and sensory properties, nutritional quality, and sustainability [2].

When discussing plant proteins and so-called alternative products made from them, it is first necessary to define what exactly is meant by the term 'plant proteins'. In principle, plant proteins are proteins, derived from plant sources. However, the food industry does not use pure proteins, but protein ingredients, which differ significantly in their protein content and in the concentration of accompanying substances. Depending on their protein content, these ingredients are classified as flours (less than 50%), concentrates (50–80%), and isolates (over 80%). A precise definition exists only for soy protein ingredients [3]. The differences in protein content are caused by the respective production processes. Flours, for example, undergo minimal processing, as the seeds are only dehulled and ground. In some cases, particularly with high-fat raw materials such as soy and lupin, a de-oiling step is also performed [4]. In protein concentrates, the protein content is further increased by grinding and air separation or by removing accompanying substances by means of extraction. The production of protein isolates undergo the most intensive processing, typically involving aqueous alkaline extraction followed by purification through isoelectric precipitation or ultrafiltration [5]. This approach allows for protein contents above 80% while simultaneously removing undesirable accompanying substances that may affect sensory properties and nutritional quality.

The protein ingredients mentioned above differ not only in their protein content but also considerably in their techno-functional and sensory properties, nutritional quality, and sustainability profile (◆ Figure 1). Price differences should also be emphasized, with flours being the least expensive, followed by concentrates and isolates being the most costly due

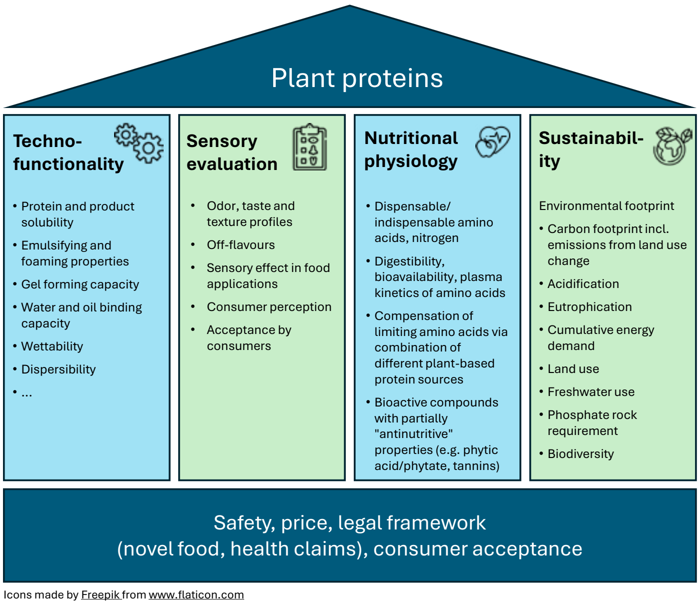

Fig. 1: **Graphical Abstract**

to the energy-intensive drying step required for their production. The food industry is willing to accept a higher price only if it is justified by the superior functionality of the ingredient.

Research on plant-based proteins is still in its early stages. The effects of manufacturing processes on their chemical composition (nutritive and potentially 'anti-nutritive' components), on their techno-functional and on their sensory properties are not yet fully understood. Additionally, the impact of different processing levels on nutritional quality remains unclear, as does the question of whether plant proteins are truly more sustainable than conventional animal proteins. Within the NewFoodSystems Innovation Space, three projects aim to shed light on these questions: 'Sustainable protein ingredients', 'AlProPlant' and 'Pr:Ins – Holistic assessment'. The findings of these projects are presented in this article. The aim is to highlight the various aspects of plant proteins that need to be considered in an objective and holistic discussion.

Plant proteins from the perspective of food technology

A variety of protein-rich raw materials are available for the production of protein ingredients. Among the most economically important are grain legumes, oilseeds, cereals, and nuts [6]. Given the many processing possibilities, a wide range of protein ingredients is commercially available, each differing in its individual properties. Standardized methods are available to assess chemical parameters such as protein content. However, for techno-functional properties, such as emulsifying ability, there is usually little or no standardized information available in manufacturers' specifications or scientific literature. This lack of data makes it challenging for food manufacturers to select the 'right' protein.

For this reason, the NewFoodSystems project 'Sustainable Protein Ingredients' conducted a comprehensive analysis of a wide range of commercially available protein ingredients, evaluating various parameters relevant to food production using uniform, standardized methods. The findings were catalogued in a database. All ingredients were analyzed for their chemical composition (dry matter content, protein content, fat content, ash content, amino acid composition), physicochemical and techno-functional properties (protein and product solubility, water and oil binding capacity, emulsifying capacity, foaming properties, particle size distribution, wettability, dispersibility) as well as their sensory characteristics. Some of these data have already been published [7]. The key results are briefly summarized here and discussed in the context of sensory properties, sustainability, and health.

Chemical composition of protein ingredients

The protein content of the analyzed ingredients ranged from 35.8 and 99.6 g/100 g dry matter (◆ Figure 2). These values were calculated using a nitrogen-to-protein conversion factor of 6.25 in accordance with legal regulations (Regulation (EU) No 1169/2011, Annex I). However, this factor tends to overestimate the actual protein content.

Differences in the protein content of ingredients derived from high-fat raw materials (soy, linseed, and sunflower) can be attributed to the direct use of the press cake or to additional processing steps such as de-oiling or aqueous-ethanolic extraction, which increase protein content [8, 9]. The protein content of protein-rich flours and concentrates from fava bean, pea, and two of the chickpea ingredients suggests that they were produced via dry fractionation [10]. This method involves ultra-fine grinding followed by air separation to separate starch granules and protein particles [11]. The yield and degree of protein enrichment in the concentrate depend on the raw material, with starch granule size being a key factor in determining its suitability for dry fractionation. Fava beans, in particular, are well-suited for this process due to their large starch granules [4]. Protein isolates (◆ Figure 2, filled symbols) from fava beans, peas, lupins, soy, rice, and potato were also

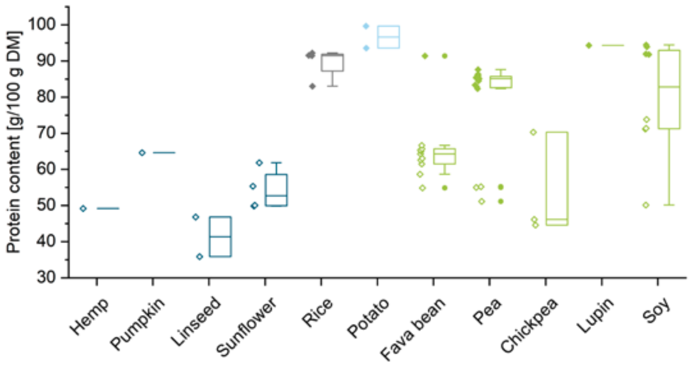

Fig. 2: **Protein content of plant protein ingredients** (n = 53)
The data points on the left side of the boxplots show the mean values of the individual ingredients.
empty symbols: protein-rich flours and concentrates; filled symbols: protein isolates
dark blue: oilseeds, grey: rice; light blue: potato; green: grain legumes
DM: dry matter [7]

investigated. These are obtained by wet processing. Variations in protein content reflect differences in raw material composition and process design [5, 12].

Protein solubility and techno-functional properties

The **protein solubility of protein ingredients** (◆ Table 1) is influenced by both the naturally occurring protein fractions in the raw materials and the processing methods applied. Particularly low protein solubility was observed in ingredients derived from the oilseed's hemp, pumpkin, linseed, and sunflower and for some soy ingredients. The main protein fractions in these ingredients are globulins, which, in their native state, exhibit high solubility in neutral and alkaline pH ranges. However, the low solubility observed in these ingredients (analyzed at pH 7) suggests that processing has led to protein denaturation, thereby reducing solubility [13]. This denaturation can be caused by thermal effects (e.g. during oil production or extraction) or exposure to solvents.
A particularly high variability in solubility was noted in dry fractionated ingredients (peas, fava beans, chickpeas). For example, fava bean concentrates displayed a wide range of solubility, from low to very high solubility. As dry fractionation is considered a mild processing method, these results suggest that subsequent treatment (e.g. thermal debittering) may have negatively affected protein solubility [14]. The highest solubility was observed in fava bean and potato protein isolates, indicating that they underwent gentle processing conditions. In contrast, the lowest solubility was found in rice protein isolate, likely due to the high glutelin content, which is known to have low water solubility [15].
Techno-functional properties encompass the **emulsifying, foaming and gelling properties** of plant ingredients. These properties are highly diverse and offer numerous advantages in food processing. The ability of plant protein ingredients to form gels, create, and stabilize emulsions and foams plays a key role in food texturization and structuring [16].
Emulsifying capacity refers to the amount of oil a protein ingredient can emulsify before the emulsion breaks. This was determined using titration and conductivity measurements [17]. Particularly low values were observed in ingredients derived from oilseeds, rice and soy. This may be due to the low protein solubility. To effectively emulsify oil, proteins must adsorb and stabilize at the oil/water interface [18]. The highest values were found for potato, fava bean and pea ingredients. However, even these did not come close to the high emulsifying capacity of some animal proteins, such as whey protein.
The **foaming activity** was determined by calculating the ratio of foam volume to protein suspension volume. The foam was generated by whipping with a stirring machine. Many plant protein ingredients showed very low foaming activity. To form foams, proteins must migrate to the water-air interface. Therefore, the low protein solubility of some ingredients may explain their low foaming activity [19]. Non-protein components can also affect foaming properties. For example, fats and lipids often have a negative impact on foam formation [20]. These may remain as residual components after mechanical oil removal (oilseeds, soy) or accumulate during the isolation process (e.g. pea protein isolates). Conversely, accompanying substances can enhance foam formation, such as saponins, which are present in fava beans [21, 22]. Among the investigated ingredients, fava bean and potato proteins exhibited the highest foaming activity.
A gel is a three-dimensional network that encloses liquids in a solid or semi-solid structure. Gel formation occurs through the cross-linking of protein molecules. Heat-induced gelation was determined by the least gelation concentration method, where the sample´s flow behavior after heating was assessed visually [23]. While animal proteins, such as gelatine and casein, are known for their excellent gelling properties, plant proteins often have a lower tendency to form gels due to differences in structure and composition. The high gelation of potato protein was remarkable, and it could therefore be used individually or in combination for the production of gel-based foods.

Sensory properties of protein ingredients

Research and industry have been working for some time to replace animal-based proteins with plant-based proteins, and numerous substitute products are already available in food retail [24]. However, simply substituting animal proteins remains a challenge, not only from a techno-functional but also from a sensory point of view. Foods containing proteins from alternative sources often differ from the usual sensory profile, which can lead to reduced consumer acceptance [25, 26]. For example, Nicolás Saraco and Blaxland [27] found that commercially available non-dairy cheese alternatives in the UK market differed from the animal-based original in several ways. These included animal, musty and brothy flavors; a yeasty, cardboard-like taste, reminiscent of onions and garlic; a drier, grainy and gritty texture; and an oily mouthfeel. A panel of testers did not categorize any of these samples as 'acceptable' [27]. In addition, plant proteins often exhibit 'beany', 'green' or 'grassy' notes [28, 29] and may have bitter and astringent flavors [30–33], which can also be perceived negatively in alternative products. Unpleasant odor characteristics stem from volatile organic compounds of various substance classes, including alcohols, aldehydes, ketones, furans and methoxypyrazines. Key compounds include 1-hexanol ('grassy', 'green'), 1-nonanol ('pea', 'vegetative', 'greasy', 'green', 'waxy'), hexanal ('green/vegetative', 'grassy', 'pea'), heptanal ('green', 'green vegetable'), and 3-isopropyl-2-methoxypyrazine ('pea pod-like', 'green pepper', 'earthy') [28, 29, 34]. These compounds are formed either through natural biosynthesis within the plant, or during processing and storage via enzymatic and non-enzymatic oxidation processes [34]. Bitter and astringent flavors are caused by non-volatile organic compounds such as saponins and polyphenols [34]. To mitigate undesirable odors and flavors, various strategies have been explored, including extraction processes to remove unwanted substances, as well as physical, enzymatic, and chemical modifications of protein structures. Additional techniques such as germination, fermentation, (hydro)thermal processing, filtration, and selective breeding have also been investigated [30, 34, 35].

A recent online survey conducted in March 2024 with 3,000 participants (aged 18 to 80) revealed that 85% of respondents considered flavor to be the most important criterion when purchasing food and beverage [36]. Therefore, it is crucial to not only select plant proteins based on their techno-functional potential for the development of novel foods, but also based on their sensory properties. For this reason, the 'Sustainable Protein Ingredients' research project also focused on the sensory analysis of the protein ingredients in aqueous suspension (2% w/w). Due to the wide variety of ingredients, botanical origins, and potential sensory attributes/descriptors, selecting the appropriate method for evaluating the proteins' sensory profiles posed a particular challenge. To address this, the Rate-All-That-Apply (RATA) methodology [37] was employed using a specially screened and sample-specific trained tasting panel. First, a comprehensive attribute lexicon was developed with the panel's input, including 76 attributes for the sensory characterization of the protein ingredients plus reference substances and attribute definitions for the sensory modalities of taste, smell, and texture. During the RATA assessment, panelists selected applicable attributes from the lexicon using a multiple-choice format after smelling or tasting each sample. They then rated the intensity of each attribute on a five-point interval scale, from 1 ("very weak") to 5 ("very strong").

Sensory analysis revealed that protein ingredients could be grouped according to botanical origin. Particularly the rice and potato protein compounds, but also the soy compounds clearly stood out from the other origin groups in terms of their sensory profiles. Rice proteins were characterized by woody, faecal, earthy, animal, musty, and straw-like notes. Potato proteins displayed sour, moldy, and potato-like odors, with a salty, sour, and astringent taste. Soy proteins, in contrast, had a sour, soy-like odor and taste, accompanied by roasted and cereal-like notes. When comparing individual protein ingredients of the same botanical origin in detail, sensory differences were found, similar to the techno-functionality tests. These differences can be attributed

		n	Protein ingredient	Protein solubility	Emulsifying capacity	Foaming activity	Gel formation
Oilseeds	Hemp	1	flour	red	red	red	red
	Pumpkin	1	concentrate	red	red	red	red
	Linseed	2	flour	red–yellow	yellow	red–orange	yellow–light green
	Sunflower	4	flour, concentrate	yellow–light green	red–yellow	red–orange	yellow
Cereals	Rice	4	isolate	red–orange	red–yellow	red–light green	red
Tubers	Potato	2	isolate	light green–dark green	light green	dark green	dark green
Grain legumes	Fava bean	11	concentrate, isolate	orange–dark green	orange–light green	red–dark green	red–yellow
	Pea	16	concentrate, isolate	red–light green	yellow–light green	red–yellow	red–yellow
	Chickpea	3	flour, concentrate	orange–dark green	yellow	red	red–yellow
	Lupin	1	isolate	light green	light green	light green	red
	Soy	8	concentrate, isolate	red–yellow	red–dark green	red–yellow	red–light green

Explanation of Tab. 1:

	Protein solubility	Emulsifying capacity	Foaming activity	Least gelation concentration
	[%]	[mL/1 g]	[%]	[%]
red	< 10	< 125	< 100	> 20
orange	10–25	125–250	100–500	17–20
yellow	25–50	250–500	500–750	13–17
light green	50–70	500–700	750–1500	8–13
dark green	70–100	700–1000	> 1500	< 8

Tab. 1: **Protein solubility, emulsifying capacity, foaming activity and gel formation of plant-based ingredients** (n = 53)
Scaling: 1. red: very low; 2. orange: low; 3. yellow: medium; 4. light green: high; 5. dark green: very high [7]

to different production processes and process parameters. As an example, ◆ Figure 3 illustrates the sensory profiles of two fava bean concentrates, which differ significantly in their flavor, but also in their smell.

Plant proteins from the perspective of nutritional physiology and human nutrition

Several factors are crucial in evaluating the nutritional quality of a dietary protein or protein-rich food. These include its protein or nitrogen content, energy value, its content of indispensable amino acids, the balance between indispensable and dispensable amino acids, and the presence of other essential nutrients (e.g. vitamins, minerals) and accompanying substances (e.g. phytate, purine nitrogen). Protein quality is primarily determined by the content of indispensable amino acids, the digestibility of the protein, and the 'bioavailability' of the released amino acids. In human studies, bioavailability is often measured by the 'plasma appearance' of amino acids after protein consumption. To meet physiological needs, daily protein intake should provide adequate amounts of indispensable amino acids [38]. The higher the protein quality of a food, the less is required to fulfil these needs. In a well-balanced omnivorous diet that meets energy and protein intake recommendations, protein quality is generally not a concern. However, in restrictive diets, such as vegan diets, protein intake, or the availability of specific indispensable amino acids, may become a 'potentially critical' factor. This is particularly relevant during life stages with increased nutritional demands, such as infancy and childhood [39, 40].
Animal protein sources, including meat, fish, eggs, and dairy products, typically have a higher absolute protein content than plant protein sources like legumes, cereals, oilseeds, and nuts. Animal proteins also tend to have a higher amino acid density (measured as indispensable amino acid content per 100 kcal of energy [g/100 kcal])[41]. In contrast, plant proteins often lack one or more indispensable amino acids. For instance, lysine is limited in cereal products, while the sulfur-containing methionine is limited in grain legumes, as the chemical analysis of the above-mentioned protein ingredients has also shown [7]. However, combining cereals and legumes can compensate for these deficiencies, resulting in a protein quality comparable to that of animal protein [42, 43].
Another key difference is digestibility. Plant proteins are generally less digestible than animal proteins due to the structural differences between plant and animal cells. Plant cells have a rigid cell wall, making it more difficult for digestive enzymes to access the proteins inside. Additional factors, such as protein structure, cross-linking via disulfide bonds, and the effects of food processing, can further influence digestion speed [38]. Moreover, plant foods contain secondary plant compounds (e.g. protease inhibitors, phytates, lectins) that may reduce amino acid and micronutrient (e.g. iron, zinc) absorption. For example, phytates can inhibit zinc absorption, promoting the German Nutrition Society to set reference values for zinc intake for adults based on phytate

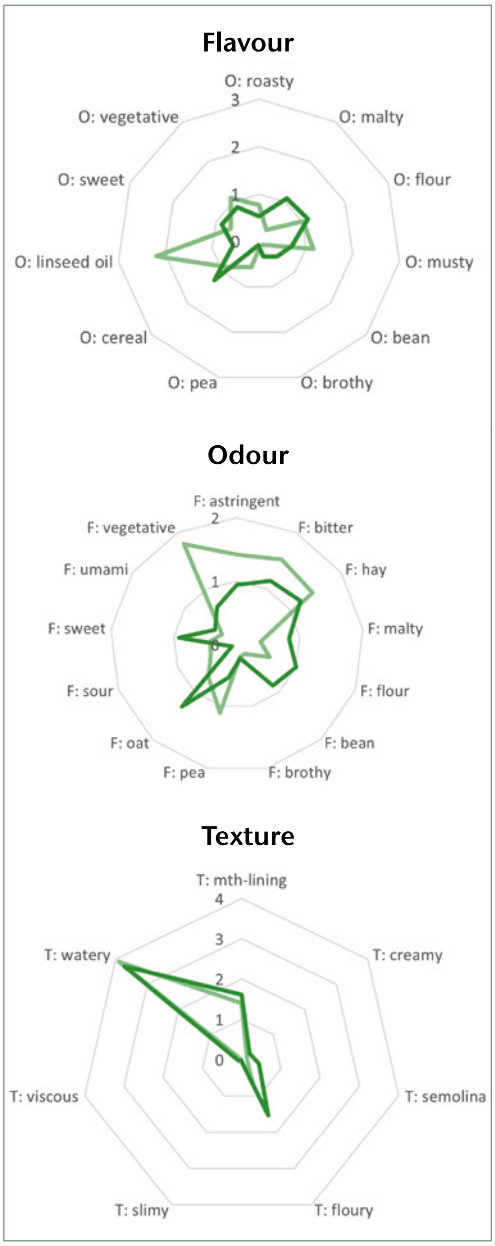

Fig. 3: **Sensory profiles of two fava bean concentrates**
Evaluated by 11 screened and sample-specific trained panelists using the Rate-All-That-Apply methodology. Mth-lining: mouth-lining

consumption levels (low, moderate, high) [44]. Secondary plant compounds can also be enriched in the plant protein ingredients through processing, which is why a comprehensive chemical analysis of the plant protein ingredients is necessary in order to be able to assess their relevance as a source of phytates.
Another aspect that should be considered in the nutritional evaluation of plant proteins is the purine content. Grain legumes such as

soy, peas, lentils, and lupins contain relevant amounts of purines, which are metabolized into uric acid [45, 46]. High purine intake can elevate serum uric acid levels, leading to hyperuricaemia which is an independent risk factor for gout [47]. However, the acute und long-term effects of plant protein consumption on purine metabolism remain unclear. Research has yet to determine how processing methods (e.g. protein extraction, precipitation) affect the purine content of plant protein ingredients. Additionally, the relationship between plant protein consumption and allergenic potential requires further investigation, as some studies suggest that a high intake of plant proteins (e.g. legumes and nuts) – common in vegan diets – may be linked to an increased risk for food allergies [48].
The extent to which different plant protein ingredients, with varying degrees of processing, contribute to adequate human protein intake remains an open question. Their physiological effects, including digestibility, absorption rates, nutrient interactions, and biofunctional properties, require further study. The NewFoodSystems project 'AlProPlant' (Alternative Proteins of Plant Origin) aims to address these gaps. One controlled nutritional intervention study within the project investigates the availability (including plasma profiles of individual amino acids) and the acceptance/tolerability of pea protein of varying degrees of processing in metabolically healthy adults. A second human intervention study examines the physiological and biofunctional effects of various plant proteins in 'complete meals', comparing them to animal proteins. This study will evaluate e.g. amino acid plasma kinetics parameters of lipid and glucose metabolism, uric acid levels, and hunger and satiety-associated parameters.

Plant proteins from the perspective of ecological sustainability assessment

Environmental footprint

As part of the NewFoodSystems project 'Pr:Ins – Holistic Assessment of Alternative Protein Sources with Special Consideration of Insects', sustainability scorecards are being developed to assess the environmental footprints of protein ingredients listed in the protein database. These scorecards are based on a series of environmental indicators derived from common impact categories used in life cycle assessment [49–51] and environmental processes identified under the planetary boundaries concept [52–54]. Given the significant environmental challenges associated with agriculture and food production, the sustainability profiles focus on key aspects, including climate change, nutrient pollution in water bodies and soils (primarily from nitrogen fertilizers), acidification, freshwater consumption, agricultural land use, and phosphate consumption due to phosphate fertilizer application. However, for simplicity and relevance to environmental policy, the following discussion will primarily focus on climate change and the carbon footprint of protein ingredients.
The preferred method for assessing the environmental footprint of a product system is life cycle assessment. This analysis considers all the production steps involved in the production of protein ingredients, from agricultural cultivation to the final product. It also includes pre-processes such as fertilizer and process chemical production. ◆ Figure 4 illustrates this approach using the example of a fava bean protein isolate, detailing the key process steps required for a comprehensive life cycle assessment.

Each process step requires specific data, which is integrated using specialized software to model the overall 'production of fava bean protein isolate' system. This data encompasses inputs – quantifying energy and resource consumption – and outputs, recording main products, by-products, wastewater, and emissions to air, water, and soil.
By processing all input and output data through the software, life cycle inventory results are obtained. These results are then multiplied by characterization factors to determine environmental impacts. For instance, climate-relevant emissions like CO_2 and methane are aggregated under the 'climate change' category by converting them into CO_2 equivalents (CO_2e) [55].

Data requirements for innovative products

For innovative products such as plant protein ingredients for human consumption, publicly available process data is often limited, especially when detailed differentiation of individual processing steps is desired across various plant-based protein raw materials and processing methods. To address this, the Pr:Ins project prioritized publicly accessible machine data sheets, converting them into coherent material flow models. These models were subsequently validated and adjusted with input from food technology experts.
Despite the generic approach, raw material-specific differences – such as variations in husk, oil, or starch content – are accounted for in the life cycle assessment (LCA) modules. These differences lead to adjustments in life cycle inventory data, influencing the environmental results.

Carbon Footprint Analysis

The carbon footprint of fava bean protein ingredients, based on the compiled data sets, is presented in ◆ Figure 5. The calculations assume that both agricultural cultivation and processing are located in Germany.

The bar charts depict the carbon footprint intensity (Y-axis) of protein ingredients (X-axis) in three processing forms: flour (F), concentrate (C), and isolate (I). For concentrates and isolates, pairs of bars represent two allocation methods: AE for 'economic allocation' and AM for 'dry matter-based allocation'. The term 'allocation' refers to the method or factor used to divide the environmental burdens between the main product and by-products (e.g. the main product, fava bean protein isolate, and the by-product, starch). Simply put, with dry matter-based allocation, each unit of mass – whether a by-product or main product – receives the same environmental burden. In contrast, with economic allocation, the mass is multiplied by the respective economic value of the by-product or main product. Since the isolate has the highest economic value, its environmental impact is consequently much higher than with mass-based allocation.

The charts show that, regardless of the allocation method used, protein isolates generally exhibit a higher carbon footprint compared to protein flours and concentrates. This increase is primarily due to additional processing steps, such as energy-intensive spray drying, which significantly elevate energy consumption and environmental impact. Similar observations have been reported in existing literature [56–58].
In general, the environmental impact of processing is lower for protein flours and dry fractionated protein concentrates compared to protein isolates. The choice of agricultural raw materials also significantly affects the outcome, as the impact increases with the higher concentration of protein relative to the same quantity of protein ingredient.
In this analysis, the transportation of agricultural raw materials from the field to processing facilities contributes minimally to the carbon footprint of protein ingredients. However, a notable contribution arises from the 'dLUC' (direct Land Use Change) component. This factor accounts for greenhouse gas emissions resulting from converting carbon-rich lands, such as forests and peatlands, into agricultural areas. It is calculated by multiplying the land requirement for a protein ingredient by a country- and crop-specific mark-up factor. Due to variations in calculation methods and data sources, these figures may differ, and in order to indicate the underlying uncertainty 'dLUC' is highlighted by a hatched pattern.

Concluding remarks

Over the last 5–6 years, plant-based proteins and their use in alternatives to animal products have become a major focus of scientific and economic interest. Whether these products offer a viable path to a more sustainable diet or whether their level of processing presents potential health risks is currently the subject of intense debate within the food and nutrition community.
From a food technology perspective, protein-rich raw materials must be processed to produce protein ingredients with customized properties that fulfil specific functions in the final product. The less processing involved (flour), the more pronounced the typical odor and taste characteristics of the raw materials, which can be undesirable in certain applications, such as dairy alternatives. Additionally, accompanying compounds, such as excessive starch content, can negatively impact the texture of plant-based drinks. To address this, suitable processing methods are required to reduce unwanted components and concentrate the protein fraction. Processing not only af-

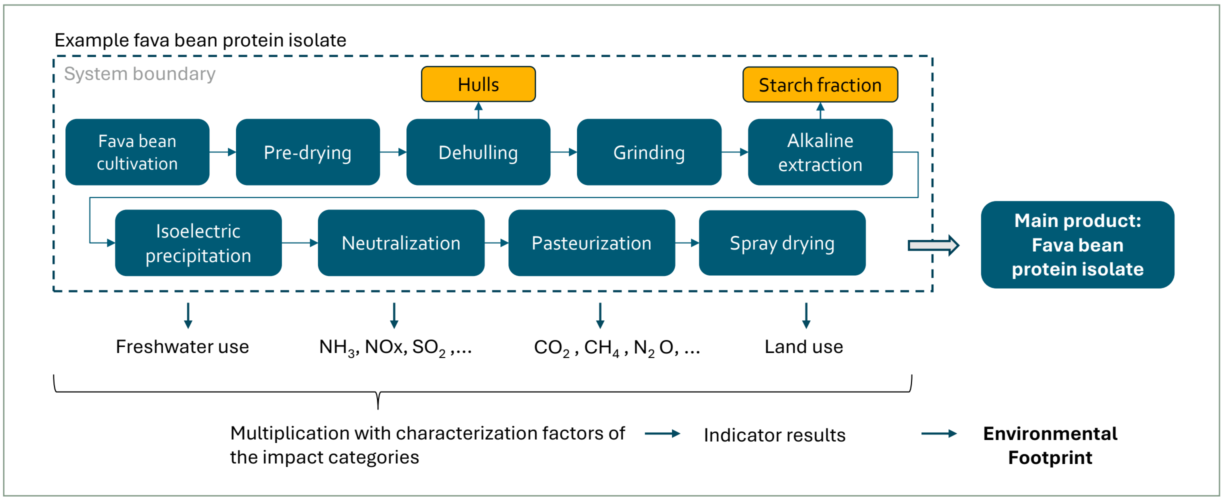

Fig. 4: **From process to environmental profile – exemplary illustration based on the production process of fava bean protein isolate** (own presentation)

fects the techno-functional and sensory properties of the ingredients but also their cost and environmental footprint.
Collaboration between agricultural and food sciences should be strengthened, as it is often still unclear which raw materials and varieties are best suited to producing protein ingredients with desirable techno-functional properties and a neutral flavor. It also remains to be seen whether entirely new varieties need to be developed – ones that are adapted to climatic conditions while meeting the requirements of the food industry.
From a nutritional physiology and human nutrition perspective, it is important to note that if animal-based foods are completely replaced by plant-based alternatives, as practized, for example, in a vegan diet, an adequate supply of some essential nutrients is not or hardly possible. The most critical nutrient in this context is vitamin B_{12}, while other potentially limiting nutrients include protein and indispensable amino acids, calcium, iron, iodine and zinc. Plant-based alternative products can contribute to nutrient intake if they are well-formulated or fortified (e.g. calcium-enriched soy drink). However, no valid statements can currently be made on the long-term effects of the (regular) consumption of plant-based alternatives on nutrient supply status, risk- and health parameters (including consumer acceptance), as there is a lack of reliable data from human intervention studies. Moreover, when evaluating nutritional patterns with plant-based alternatives regarding their physiological impact (e.g. nutrient supply), the entire food selection from the various food groups should be taken into account, rather than evaluating the impact of a single food stuff alone.
The market for plant-based proteins and derived foods is highly diverse. However, the majority of these products have not yet been included in established nutrient databases (e.g. *Bundeslebensmittelschlüssel*), making it difficult to analyze dietary intake in intervention and observational studies. This particularly affects the estimation of indispensable amino acids and essential micronutrients, complicating the nutritional evaluation of plant protein ingredients and their contribution to human nutrition.
From an environmental sustainability assessment perspective, it is evident that the climate footprint of the protein ingredients – and, in principle, their overall environmental footprint – rises with increasing protein enrichment. The ´jump´ from concentrate to isolate is particularly significant. If one assumes that the economic value of an ingredient increases with its protein content per unit mass, and this factor is accounted for through the economic allocation of environmental impacts, the differences become even more pronounced – extending even to the comparison between flour and concentrate.
On the other hand, analyses of protein ingredients have shown that protein functionality (techno-functionality and sensory properties) can be more precisely tailored to product applications as protein enrichment progresses. Consequently, protein concentrates and isolates are likely to play an increasing role in the production of protein-rich foods in the future. It is therefore crucial to minimize the specific environmental impact associated with

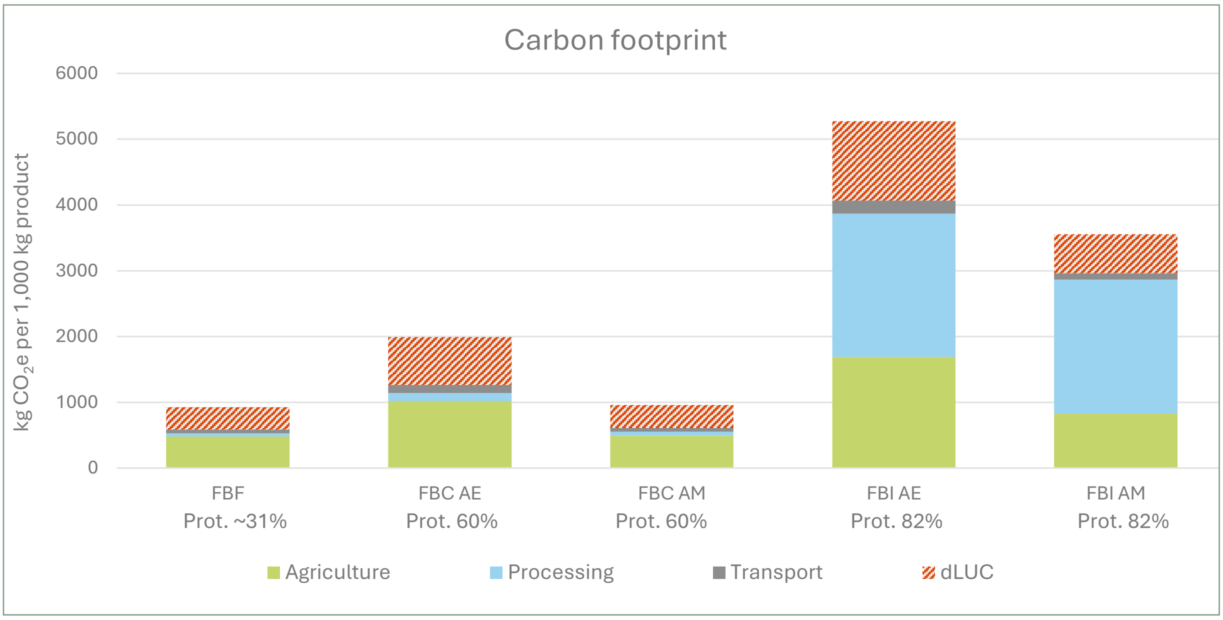

Fig. 5: **Carbon footprint of fava bean protein ingredients**
AE: economic allocation; AM: allocation by dry matter; dLUC: stands for 'direct Land Use Change' and identifies greenhouse gas emissions in connection with direct land use changes in the graph; FBC: fava bean protein concentrate; FBF: fava bean flour; FBI: fava bean protein isolate; Prot: protein content in the product (fresh mass)

these ingredients. One approach could be the high-value utilization of side streams, redirecting them into food production rather than animal feed. Another important factor is improving energy efficiency in energy-intensive processing steps such as spray drying. However, the development and production of appealing foods from minimally processed protein ingredients should not be overlooked, as this naturally generates fewer by-products and has the lowest environmental impact.

The interdisciplinary approach presented in this article highlights the tensions, opportunities and challenges involved in developing plant protein ingredients and the foods derived from them. In summary, plant proteins offer enormous potential but still require extensive research and development. The successful integration of techno-functionality, sensory properties, nutritional quality, and sustainability is crucial to meet growing consumer demands and global challenges. In addition, so-called alternative products can make a significant contribution to promoting and implementing a more plant-based dietary pattern.

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More information at
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The authors declare that there is no conflict of interest. AI was used for language optimization and to create/check translations.

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