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Value chain gaps in plant-based protein production in Europe – A literature review

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Co-funded by the European Union

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Abstract:

This report examines the dynamics of the plant-based protein value chain in Europe, encompassing facets from cultivation to sales and retail. We explore challenges in crop management, pest and disease control, harvesting, and gaps in farming knowledge across different legumes i.e. lupins, pea, faba bean, chickpea, lentil and soybean. We found regional disparities in the availability of plant protection products and suggest targeted strategies to bridge these gaps. The cultivation and production section identified the need to tailor farming knowledge to regional conditions, emphasizing the diverse challenges with growing grain legumes by farmers.

In the domain of production we uncover regional variations in yield and persistent yield gaps in lupin, pea, faba bean and soybean and lower yield stability compared to winter sown cereals. Challenges in farming knowledge, climate conditions, and the availability of adapted varieties and plant protection products to enhance the competitiveness of the plant-based protein sector need to be addressed by public and private actors.

Processing and packaging challenges are explored, revealing inadequacies in infrastructure, outdated processing facilities, and limited innovations in extraction methods. Specific limitations in processing individual legume species are described and require comprehensive approaches involving technological innovation and sustainable practices throughout the value chain.

In the marketing and distribution we identified certification and standardization challenges, branding obstacles, and transportation inefficiencies. The report emphasizes the need for harmonization in certification processes, transparent adherence to standards, and strategic branding to build trust and facilitate the seamless distribution of plant-based products in the EU.

Sales and retail challenges are scrutinized, ranging from limited consumer awareness and uncertain preferences to pricing inconsistencies and some resistance to plant-based diets. The report details the market dynamics for various legume species, highlighting the hurdles for market acceptance for these crops. The impact of brand withdrawals due to financial constraints and market uncertainties is explored, highlighting the volatile nature of consumer demand in the plant-based protein sector.

Despite the challenges identified, sustainability emerges as a key driver supporting the inclusion of more legumes in Europe especially for organic production, to reduce carbon footprints, and ethical practices gaining attention. We conclude by emphasizing the need for collaborative efforts, educational initiatives, and strategic communication to overcome challenges and foster a resilient and flourishing plant-based protein industry in Europe.

Dissemination Level		
PU	Public, fully open, e.g. web	X
SEN	Sensitive, limited under the conditions of the Grant Agreement	
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Title: new VALue landscapes for plant PROtein Pathways
Type of action: HORIZON Innovation Actions ● Topic: HORIZON-CL6-2021-FARM2FORK-01-02
Start date of project: 01 September 2022 ● Duration: 48 months

"This project receives funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101059824."

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1. Introduction

Value chains of protein crops in Europe refer to the interconnected set of activities and actors involved in producing, processing, and distributing protein-rich crops, from the farm to the consumer[1,2,3]. The aim of a sustainable value chain is to create value for all actors involved, including delivering a product of acceptable quality to consumers[4,5]. Within Europe, the protein value chain should ensure a secure and sustainable supply of protein for both animal and human consumption[2,4]. Applying the value chain concept can emphasise the importance of collaboration and coordination among the various stakeholders involved in producing and distributing protein crops[2,5]. By working together, stakeholders can identify opportunities to improve efficiency, reduce inputs and costs, improve sustainability attributes, and respond to market needs, ultimately increasing the value of the final product[1,6]. The value chain concept also recognises the importance of sustainability, quality, and safety in ensuring the long-term success of the protein crop industry in Europe[5,6,7].

Lock-in or gaps in the value chain of protein crops in Europe refer to factors that are preventing the sustainable production, processing, distribution and consumption of protein crops in the region[3,5,6]. These factors may include structural, regulatory, economic, technological, social, cultural or institutional barriers that limit the growth and development of the sector[6,8]. Lock-ins can occur when there is a lack of competition or innovation in the market, leading to a stagnant or declining sector[7,9,10]. Gaps, on the other hand, can refer to missing links in the value chain, such as inadequate farm inputs such as seeds[5,11], suitable soil, challenging climate conditions[1,5,11], and limited herbicides[8], pesticides[8], fertilizers[6], and harvesting machinery[12,13]. It also comprises inadequate infrastructure or limited research in cultivation, processing, packaging[14], transportation and marketing, which hinders the efficient movement of protein crops from farm to market[8,12].

Protein crops such as lupins, pea, faba bean, chickpea, lentil, and soybean are crucial in Europe for their high protein content and further quality characteristics, offering versatility in consumption as whole foods or processed into various products, including flour[15,16], protein powders and isolates[15,17], and meat and dairy substitutes[18,19]. Their incorporation into the human diet not only enhances nutritional balance and diminishes reliance on conventional meat-based proteins but can also address environmental concerns due to their lower greenhouse gas emissions and land use compared to traditional animal-based sources[9,20]. Moreover, being predominantly legumes, these crops contribute to nitrogen fixation in the soil, reducing the need for synthetic fertilizers and improving soil health, thereby positively impacting yields and overall crop performance[8,21]. Additionally, when integrated into crop rotations, protein crops aid in breaking disease and pest cycles, reducing weed pressure, and enhancing soil structure and fertility[11,13,20]. This aligns with regenerative agricultural practices for climate change mitigation and biodiversity protection. Beyond ecological benefits, these crops constitute a significant income source for farmers and stakeholders in the value chain[6,22], collectively fostering sustainable and diverse agriculture in Europe while providing essential nutritional advantages[11,21].

In this context, it is crucial to identify the lock-ins and gaps within the value chain at the European level[7,18]. This entails enhancing access to seeds, elevating productivity, improving quality, fostering innovation, reducing waste, cultivating markets for regionally grown legumes, and advocating sustainability[7,9]. Furthermore, by advocating for the regional production, processing, and distribution of protein crops, the carbon footprint associated with transportation and storage can be minimized[7,18]. Promoting domestic production offers economic advantages to farmers and fosters a diverse and resilient food system[9,11].

2. Methodology

This report was developed through a meticulous literature search conducted by ZALF and Teagasc. The primary objective was to establish a robust conceptual and methodological framework that could effectively identify bottlenecks and deficiencies within the European protein crop value chain. The focus of the literature review was on uncovering gaps and constraints at the European level, with specific attention given to variations in different pedoclimatic regions, including Atlantic Europe, Central Europe, and Southern Europe. Additionally, a detailed analysis was conducted for some individual countries to ensure a nuanced understanding of the challenges.

To maintain a systematic approach, a value chain mapping methodology, following the principles outlined by Heery et al. (2017[23]), was employed. The value chain framework was made up of five primary activities comprises (1) farm inputs, (2) cultivation & production, (3) processing & packaging, (4) branding, marketing, & distribution, and (5) sales and retails. The value chain actors and institutional context was also included in this framework. The value chain was described considering six targeted protein crops: lupins, peas, faba beans, chickpeas, lentil, and soybeans. This approach aimed to provide a comprehensive understanding of potential regional lock-ins and gaps specific to these crops in Europe.

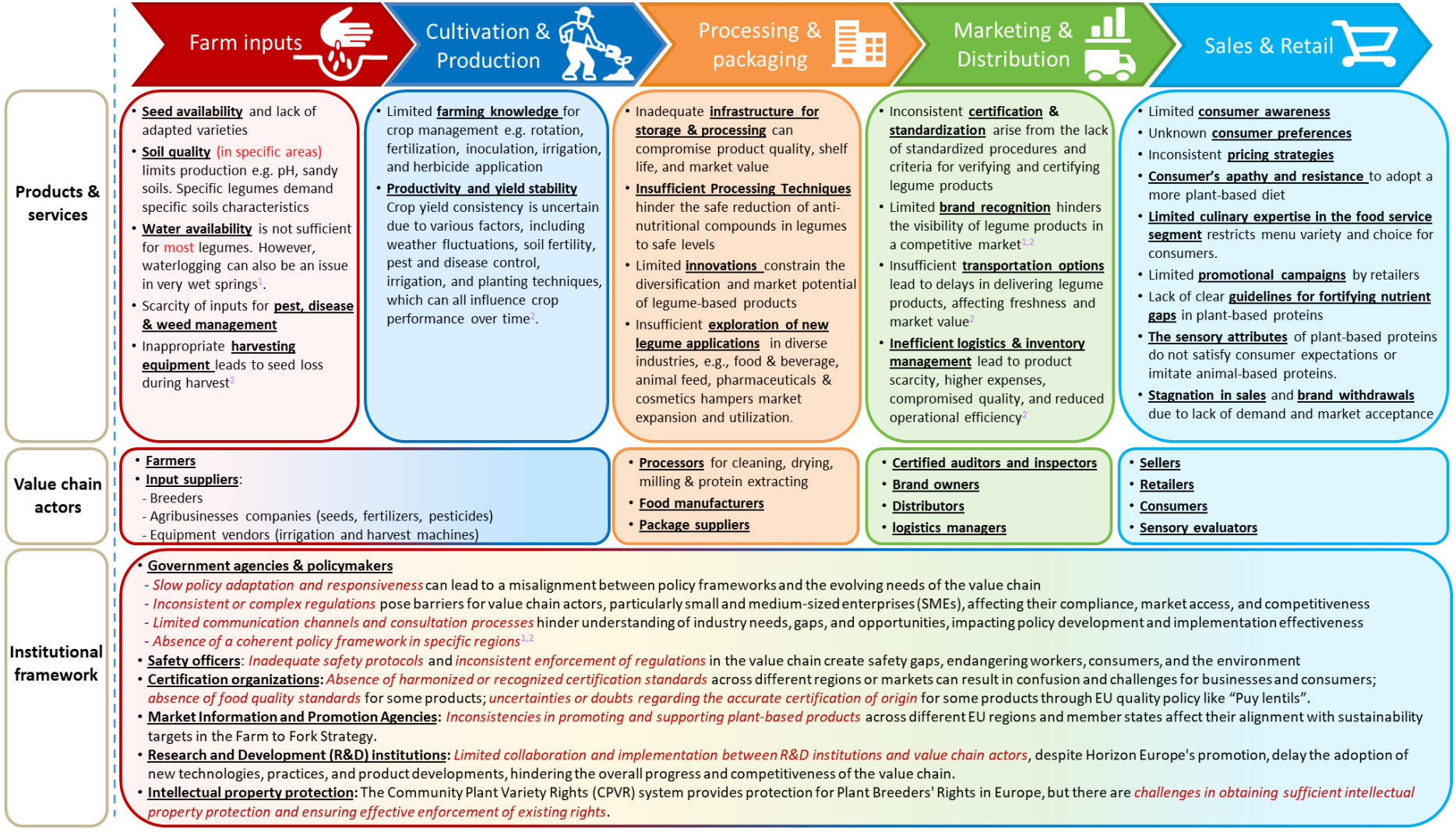
This report employed a comprehensive and iterative methodology to investigate the European protein crop value chain. The research began with an initial categorization, differentiating between academic literature and grey literature, totaling 166 references. The academic literature search spanned databases, journals, and repositories, providing a scholarly foundation. Emphasis was placed on outputs from EU-funded projects (e.g., LEGValue[22,7,18,24], TRUE[1,8,25], and Legumes Translated[11,26]) and public engagement activities by entities like EIT-Food[9,27] to capture both academic and practical perspectives. Grey literature, including reports from the European Commission and national strategies, was systematically included for policy insights[21,28]. Documents based on expert analyses from forums like the EIP Agri Focus Group on Protein Crops and The Legumes Expert Forum of DAFA contributed practitioner perspectives. Interviews with experts and targeted data collection efforts enhanced the report's depth. The methodology was iterative, fostering continuous review and synthesis of information from diverse sources to construct a nuanced understanding of the European protein crop value chain.

Moreover, the report benefited from valuable insights obtained through interviews, ensuring a holistic understanding of the challenges and opportunities within the European protein crop value chain. These interviews provided a qualitative layer to the research, offering perspectives from key stakeholders and experts involved in various segments of the value chain. Additionally, specific data collection efforts were undertaken to inform graphical representations, such as the comparison between wheat and legume varieties depicted in the story map. This involved gathering data on different varieties of wheat and legumes, analyzing their distribution and adoption, and synthesizing the information into visually accessible formats for enhanced storytelling. The collaborative integration of these diverse sources, interviews, and data collection processes contributes to the depth and richness of the insights presented in this report.

Based on the findings and analysis provided in this report, and the addition of insights from interviews with relevant actors in the value chain, and a stakeholer workshop, an interactive story map was produced and is available online:
https://storymaps.arcgis.com/stories/281fbecc069d46bf966289284d0ccd55

3. Results

We present a comprehensive analysis of the gaps observed across various stages of the value chain for legume-based crops (**Figure 1**). Our investigation encompasses critical stages, including farm inputs, cultivation and production, processing and packaging, marketing and distribution, sale and retail, as well as the involvement of key value chain actors and the institutional framework. The figure vividly illustrates the discrepancies identified at each stage, shedding light on the specific challenges and inefficiencies encountered within the legume value chain. By delineating these gaps, our findings aim to provide a nuanced understanding of the areas requiring targeted interventions and improvements. This visual representation serves as a valuable tool for stakeholders and policymakers to devise strategic initiatives that can enhance the overall efficiency and sustainability of the legume-based crop value chain. The following sections provide more detailed commentary on the points made in the figure.



The gaps are relevant to all of Europe if there are no numbers mentioned. Otherwise, numbers mentioned in specific cases refer to the **Atlantic Europe**[1], **Central Europe**[2], and **Southern Europe**[3]

***Figure 1**: Mapping gaps in the protein crops value chain across Europe. The use of red text in certain sentences is intended for emphasizing or highlighting specific portions of the text, drawing attention to key messages or details. Meanwhile, black text signifies the main body of the sentence or provides general information.*

3.1. Farm inputs

Gaps in essential farm inputs, spanning from seed availability[29,30] and soil quality to water access, plant protection products, and harvest equipment, can significantly impact the value chain of plant-based proteins (**Figure 1**). Particularly in the context of cultivating diverse legumes like lupin, peas, fava beans, chickpeas, lentil, and soybeans across various European regions, these input gaps can lead to reduced yields, decreased crop quality, and increased production costs[31]. Moreover, these gaps pose a threat to the reliability and consistency of the supply chain, ultimately influencing the pricing and availability of plant-based protein products. This perspective aligns with the key messages outlined in the story map, emphasizing the distinct challenges and considerations related to legume cultivation in the European context.

3.1.1. Seed availability

In Europe, cereals have been prioritized, taking precedence over legumes, which has led to the relegation of legumes primarily for animal feed[32]. Consequently, this prioritization has led to the underdevelopment of legume breeding, contributing to the suboptimal quality of seeds[32]. The scarcity of legume seeds, evident in the limited number of registered varieties[29,30] influenced by breeding programs[30], certified seed quantities[29,31], and the area designated for seed production[29], poses a significant challenge for the production of plant-based protein from grain legumes. To comprehend this disparity, it is valuable to examine the differences across European regions and compare them with wheat, a well-established crop throughout the continent (**Figure 2A,D & G**).

In Northern Europe, although there is a preference for legume varieties that can endure cold conditions, the average number of registered varieties is comparatively lower. This may be due to a concentration on a specific subset of cold-resistant varieties, resulting in a more limited pool of registered varieties, in contrast to the broader diversity found in regions with different climatic preferences (**Figure 2A**). Conversely, Central Europe, characterized by diverse climates, requires adaptable grain legume varieties (**Figure 2B**). Similarly, the southern European region demands heat-tolerant grain legume varieties, reflecting its warmer climate (**Figure 2C**). Seed availability varies significantly based on the crop within individual countries, emphasizing the diverse agricultural landscape in Europe. For instance, winter wheat boasts an extensive 172 registered varieties, underlining a considerable gap in knowledge and expertise related to seed production and breeding in the legume sector in the European context[7,11,30].

The challenge is not the same across all legumes owever. Lupin seeds pose difficulties for farmers in obtaining quality seeds[33,34]. Conversely, peas have abundant varieties for diverse growing conditions[11,35,36]. High-quality faba bean seeds present challenges due to limited cultivation and the presence of only a few specialized seed companies[11,37]. Although chickpea seeds are relatively scarce, some companies have started offering them as the crop gains popularity among farmers[11,29]. Similarly, lentil face availability challenges but witness emerging seed companies, driven by the crop's recognized nutritional benefits[29,38]. In contrast, soybeans, widely cultivated, have various varieties for different conditions[11,29]. These variations in seed availability contribute to differing levels of production and value chain efficiency in Europe. As illustrated in **Figure 2B, E & H**, the contrast is particularly notable when comparing to a staple crop like wheat, which benefits from a well-established and stable seed supply network, ensuring more consistent performance throughout the value chain.

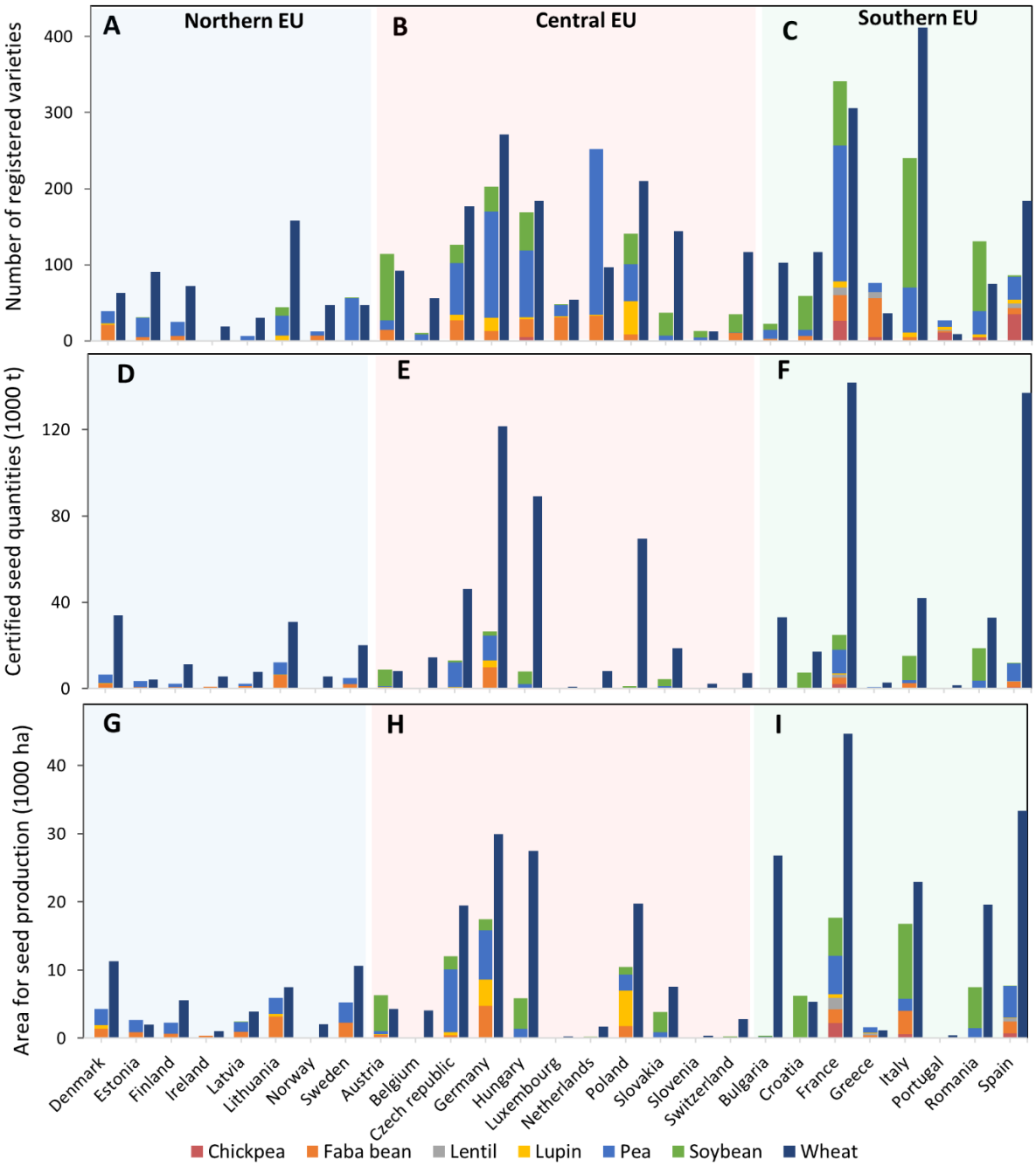


***Figure 2**: Total varieties listed on EU countries' national variety catalogues in 2023 (panel A, B, and C; EU Plant Variety Database[39]). Information on chickpeas and lentil was sourced from respective national catalogues[29]. The amount of certified seed quantities (panel D, E, and F) and area for seed production (panel G, H, and I) of certain legume crops compared to wheat between 2000 and 2022 in the EU member states (European Seed Certification Agencies Association, ESCAA[40]; Online Database).*

3.1.2. Soil quality

The quality of soil, including factors like pH levels and soil type (e.g., sandy soils), exhibits significant variation across different European regions, impacting the sustainability of various crops, including specific protein-rich legumes such as peas, chickpeas, lentil, lupins, soybeans, and faba beans[11,41]. These legumes often have distinct soil requirements crucial for their ecological balance and resilience, emphasizing the importance of aligning the right legume with appropriate soil conditions to enhance the overall sustainability of agricultural practices in the value chain.

Exploring the soil preferences and sustainability contributions of diverse legume crops, including lupins, peas, faba bean, chickpeas, lentil, and soybeans, unveils a nuanced understanding of their unique adaptations to European soil conditions. Lupins, recognized for their nitrogen-fixing properties, thrive in nutrient-poor soils but are highly sensitive to acidity, preferring a neutral to slightly acidic environment[41,26]. Given the soil acidity variations across Europe, careful monitoring of soil pH is necessary for successful lupin cultivation, considering specific conditions throughout the region[11,42]. Peas, considered a relatively undemanding crop, tolerate various soil types but achieve optimal growth on well-drained, well-aerated soils with a neutral to slightly alkaline pH. Faba beans, also relatively undemanding, prefer deep, well-drained soils with good water retention capacity but are sensitive to acidity[43,44,45]. Chickpeas exhibit adaptability to a broad range of soil types but thrive particularly in well-drained soils rich in organic matter. Sensitive to waterlogging and unsuitable for heavy clay soils, chickpeas contribute to sustainable practices by promoting soil health and minimizing environmental impacts[46,47]. Lentil prefer well-drained soils with a neutral to slightly alkaline pH, necessitating good organic matter content and nitrogen availability for optimal yields. They contribute to sustainability by promoting biodiversity and reducing the need for synthetic inputs, with considerations for conditions across Europe[48]. Soybeans demand well-drained, fertile soils with a pH between 6.0 and 7.5 and are sensitive to waterlogging and unsuitable for heavy clay soils. High nutrient requirements, especially for nitrogen and potassium, underscore the importance of soil quality in soybean cultivation, contributing to the overall sustainability of agricultural ecosystems[49,50].

3.1.3. Water availability

In numerous European regions, cultivating legumes faces challenges due to inadequate water during critical stages, despite the drought tolerance observed in certain species and varieties. on the other hand, unpredictable weather patterns and the potential for waterlogging, especially during excessively wet springs in northern regions, can significantly affect legume production. Implementing effective water management practices and adaptation strategies is essential to overcome these challenges and ensure a sustainable and dependable supply of protein-rich legumes.

Shifting the focus to specific crops, lupin, known for its drought tolerance, highlights the importance of maintaining sufficient soil moisture during germination and early growth stages for optimal yields[41,51,26]. Across Europe, lupin cultivation typically occurs in regions with moderate rainfall, such as the northeastern parts of the continent[52,53,54]. Peas, requiring adequate soil moisture during early growth stages, may experience potential yield reductions under water stress[55,56]. Throughout Europe, pea cultivation is concentrated in regions with moderate rainfall. However, drought occurrences in these areas may adversely impact yields. Faba beans, an essential legume in Europe, exhibit higher water requirements than other legumes and thrive in heavy soils capable of storing water. While they are relatively drought-tolerant, optimal yields emphasize the need for sufficient soil moisture during early growth stages[45]. Cultivation is predominantly found in European regions with higher rainfall, although concerns about water availability may arise in dry years or areas with low rainfall[11,57]. Chickpeas, adapted to warm and dry climates, have lower water requirements compared to other crops, but ensuring adequate soil moisture during early growth is crucial for high yields[57,58]. Across Europe, chickpea cultivation is still relatively limited. Lentil, known for their relative drought tolerance, can adapt to low rainfall conditions, yet sufficient soil moisture during early growth stages is critical for optimal yields[57]. In Europe, lentil cultivation is concentrated in regions with varying rainfall levels. Soybeans, relatively water-demanding, require adequate soil moisture throughout the growing season[11,59]. Across Europe, soybean cultivation is primarily concentrated in regions with

higher rainfall. However, drought occurrences in these areas may negatively affect yields[11,59], especially during critical stages like flowering and pod filling[60].

3.1.4. Pest and disease management

The scarcity of registered plant protection products for protein-rich legumes in Europe, in comparison to staple crops like wheat, poses challenges (**Figure 3**). This gap in pest and disease management can lead to reduced yields[11,12], higher production costs, lower quality and potential impacts on the availability and pricing of plant-based protein products in the EU, affecting the industry's sustainability. The extent to which pests and diseases represent a problem for these crops varies depending on the specific crop and the location within the EU region (**Figure 3**). In 2023, an analysis of the registered products for various legume crops, including lupin, pea, faba bean, chickpea, lentil, and soybean, in comparison to wheat, across diverse European regions illuminated regional variations in product availability (**Figure 3**). The results unveiled a persistent pattern of comparatively low average registered products for different legume crops when compared to wheat, with Northern Europe presenting the lowest figures, followed by Southern Europe. Interestingly, Central Europe stood out with a higher number of registered plant protection products for the specified legume crops. This assessment underscores the regional disparities in the availability of plant protection products for legumes, emphasizing the need for targeted strategies to address these discrepancies.

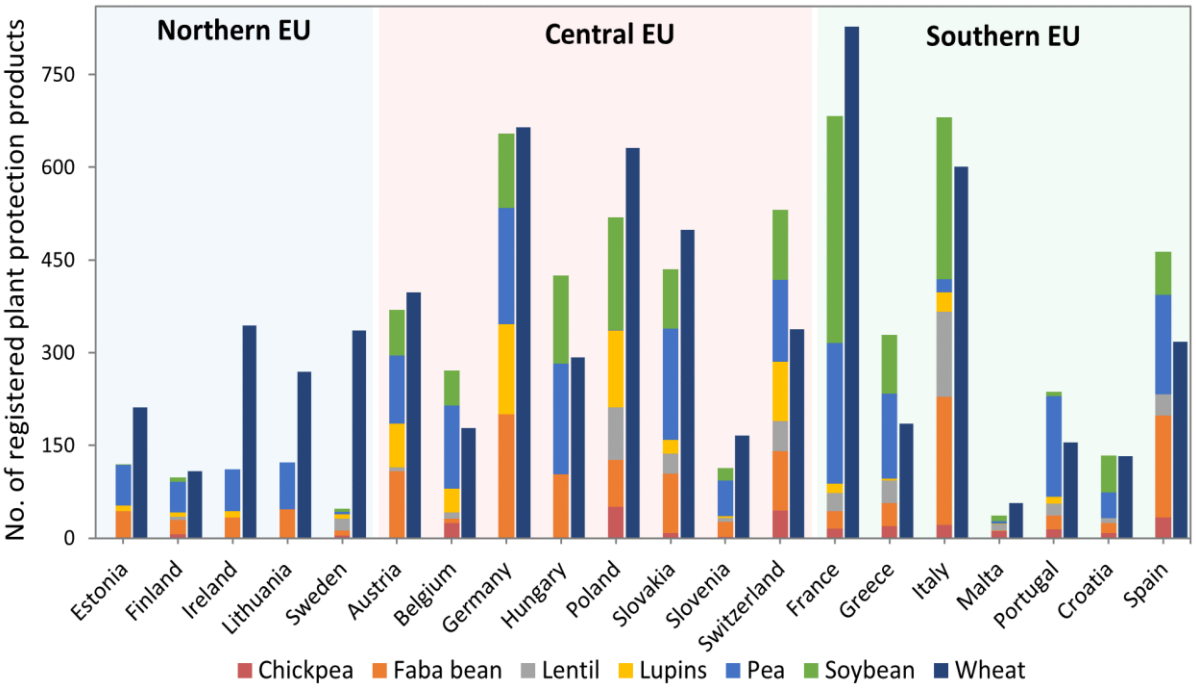


***Figure 3**: Number of registered plant protection products for some legume crops in comparison with wheat, in various regions of the EU[61] 2023.*

Protein-rich legumes such as lupins, peas, faba beans, chickpeas, lentil, and soybeans each face unique challenges in pest and disease management. Lupins are susceptible to a variety of pests and diseases, including fungal diseases like anthracnose and root rot, and insect pests such as aphids and bean weevils[51,53,62]. Peas encounter issues with fungal diseases such as powdery mildew and insect pests like pea weevils and thrips[55,45,62]. Faba beans face susceptibility to various pests and diseases, including fungal diseases like chocolate spot and insect pests such as bean aphids and thrips[45,62,63]. Chickpeas are susceptible to a range of pests and diseases, including fungal diseases like Ascochyta blight and insect pests such as pod borers and aphids[62]. Lentil share susceptibility to fungal diseases such as Ascochyta blight and insect pests like aphids and pod borers[48,62]. Soybeans, like the

aforementioned legumes, are susceptible to a range of pests and diseases, including fungal diseases such as soybean rust and insect pests such as stink bugs and soybean aphids[62,64]. Across Europe, the cultivation of each of these legumes is still relatively limited, with corresponding research on pest and disease management strategies also being limited and specific to the European context for each crop[11,65,42].

3.1.5. Harvesting equipment

Harvesting equipment poses unique challenges for legumes in Europe, and the specific requirements vary based on both the type of crop and the geographical region. Lupin and soybeans, for instance, share a commonality as they are conventionally harvested using traditional combine harvesters[26,66,67]. However, lupin faces distinctive challenges due to the susceptibility of its seeds to shattering during harvest, prompting ongoing research in Europe to explore specialized harvesting technologies[68]. On the contrary, peas, faba beans, chickpeas, and lentils exhibit differences in their harvesting methods. Peas, being delicate, necessitate precision to achieve the appropriate maturity stage, and various harvesters, including self-propelled, tractor-mounted, and combine harvesters, are available[69,70,71]. Faba beans, harvested with traditional combine harvesters, encounter challenges related to the brittle nature of their seeds[72]. Chickpeas, characterized by delicate plants, require careful handling during harvesting, and a variety of harvesters, including combine, self-propelled, and tractor-mounted options, are available[73,67,74]. Lentil, with their delicate nature, necessitate harvesting at the appropriate maturity stage, and various harvesters, including self-propelled and tractor-mounted options, are used[75,76]. In summary, while lupin and soybeans share a common harvesting method, the specific and varied harvesting requirements for peas, faba beans, chickpeas, and lentil underscore the necessity for diverse approaches in legume agriculture to meet the distinct needs of each crop.

3.2. Cultivation & Production

3.2.1. Farming knowledge

The knowledge gap in crop management, encompassing rotation, fertilization, inoculation, irrigation, and herbicide application, poses a significant challenge for cereal legumes in Europe (**Figure 1**). This deficit can lead to diminished yields, lower quality, and increased production costs, thereby impacting the availability and pricing of plant-based protein products in the EU[32]. To enhance industry resilience and sustainability, addressing this knowledge gap through comprehensive education, training, and advisory support is crucial. Each crop, such as peas, with its specific requirements in contrast to lupins, demands tailored approaches to management.

Legume crops such as lupin encounter varied challenges across different regions of Europe, impacting farming knowledge and practices[11,24,77]. It is crucial to recognize that the differences in farming knowledge and practices apply to all legume crops. However, it is essential to note that the body of knowledge concerning legumes, and consequently the capacity to address these challenges, is comparatively more limited than for other crops (e.g., cereals). In Northern Europe, colder climates necessitate specialized knowledge to address issues related to frost tolerance and shorter growing seasons. Conversely, Central Europe, experiencing mixed climates, requires navigating diverse conditions and adapting to varying soil types. Southern Europe faces challenges associated with warmer and drier climates, requiring expertise in water management, heat stress mitigation, and specific soil requirements[54,53,26]. Pea cultivation, spanning Northern to Southern Europe, encounters climate-related challenges such as cooler temperatures in the north and heat stress in the south[78,79,80]. Adapting cultivation practices to these regional nuances is imperative, necessitating a tailored

knowledge base for optimal pea cultivation and inoculation requirments[81,82]. Faba bean production, especially in Central Europe, faces challenges due to limited access to suitable varieties[37,79] and management practices, influenced by fragmented land use[4,13,83]. Chickpea cultivation, predominantly constrained to warmer regions in Central and Southern Europe, encounters challenges related to a warm and dry climate. Limited access to high-quality seed varieties and specialized equipment further constrains productivity[29]. Lentil cultivation, seeing renewed interest in Central and Northern Europe, requires knowledge of a cool and moist climate. However, limited access to high-quality seed varieties and specialized equipment hampers productivity, highlighting the need for targeted initiatives to bridge these gaps[38,84,85]. Soybean cultivation, extending to Central and Southern Europe, faces challenges related to a warm and moist climate. Similar to other legumes, limited access to high-quality seed varieties and specialized equipment poses challenges, emphasizing the importance of region-specific knowledge[7,86]. These insights underscore the necessity of tailoring farming knowledge to diverse regional conditions, promoting sustainable and efficient cultivation practices across Europe.

3.2.2. Production, yield stability and yield gap

While legumes hold significant potential as valuable sources of plant-based protein, their production levels often fall short of their biophysical potential in various European regions, i.e. there is a yield gap in legumes that varies across different regions of Europe[87,88] (**Figure 5 and 6**). Factors contributing to this gap encompass a range of challenges as outlined above, including limitations in farming knowledge and practices related to crop management[20,52], varying soil and climate conditions, insufficient availability of registered plant protection products for pest and disease management, and issues related to seed quality and availability.

Over the past decade (2013-2022), an examination of lupin, pea, faba bean, and soybean production in comparison to wheat across various European regions sheds light on regional disparities in crop output (**Figure 4**). The findings revealed a consistent trend of relatively lower average production for different legume crops compared to wheat, with Northern Europe exhibiting the lowest production, followed by Central Europe and Southern Europe. Notably, several legume crops, including chickpeas and lentil, showed negligible or no production across most regions. In Central Europe, some legume crops exhibited noticeable production, yet chickpeas and lentil remained absent. Despite observed productions of different legume crops in Southern Europe, the averages still lag behind those of wheat. This regional breakdown provides insights into the existing gaps in legume production, emphasizing the need for targeted interventions to enhance the role of legumes in European agriculture.

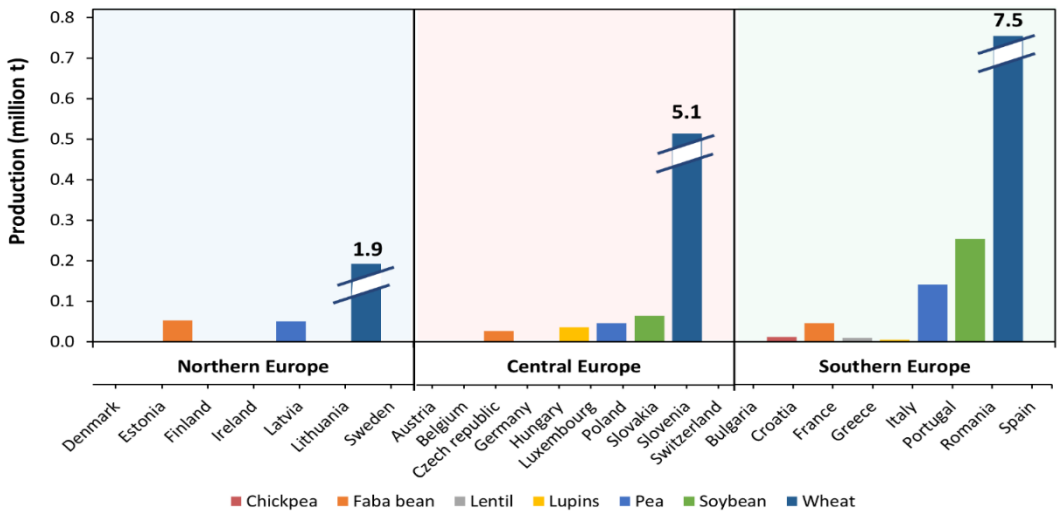


Figure 4: Production of lupin, pea, faba bean, and soybean in comparison to wheat, across different regions in Europe in the last 10 years, from 2013-2022; data source FAOSTAT[87].

Conducting a yield gap analysis is crucial for gaining insights into the dynamics of the plant-based protein value chain in the EU, particularly for crops like soybean (both irrigated and rainfed), peas (rainfed), and faba bean (rainfed)[88,89] (**Figure 5**). This analysis helps to identify and understand the challenges these crops encounter in realizing their maximum yield potential. Addressing these yield gaps becomes pivotal in ensuring a consistent and sustainable supply of plant-based protein products in Europe. To enhance the growth and competitiveness of the plant-based protein sector in the European market, it is imperative to bridge these yield gaps through the implementation of improved agricultural practices and supportive mechanisms.

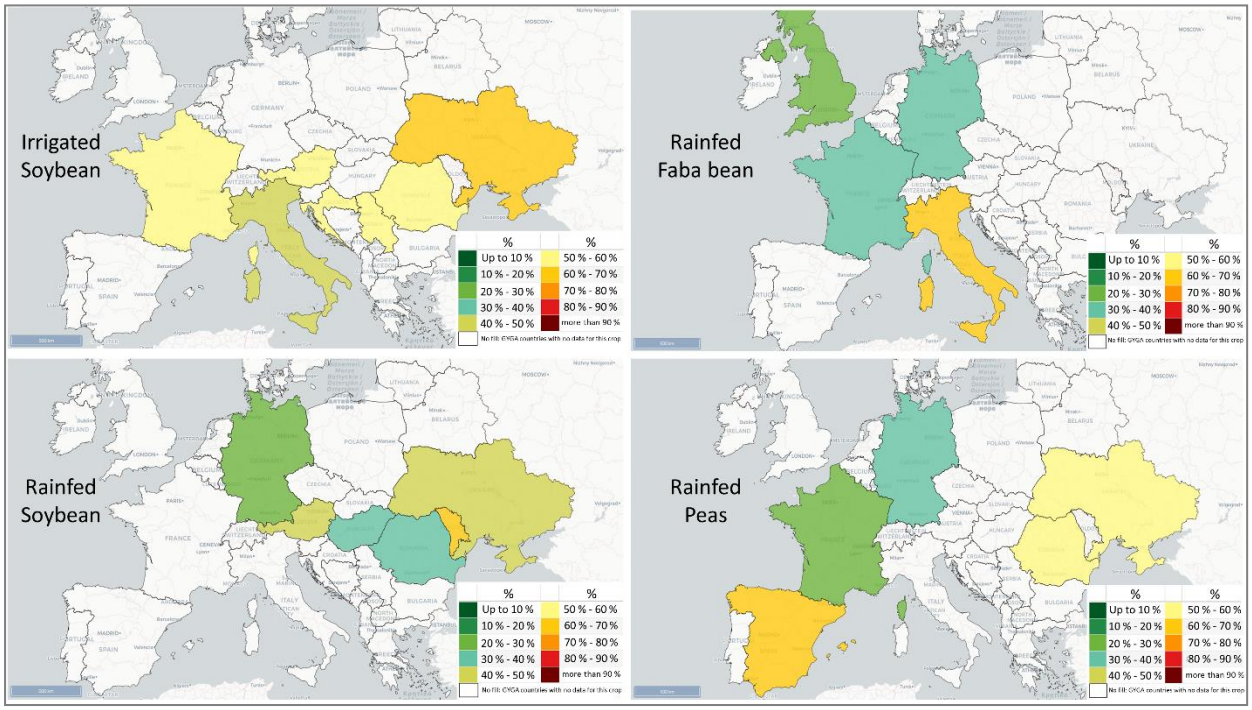


Figure 5: The relative yield gap for different protein crops in Europe. The yield gap describes the difference between the yield potential and the actual achieved yield. Extracts from the Global Yield Gap Atlas[88]; Used with friendly permission from Global Yield Gap Atlas under CC BY-NC-SA 4.0.

3.3. Processing and packaging

The substantial expenses associated with establishing and maintaining production infrastructure, including both facilities and equipment, present formidable obstacles for plant-based food manufacturers in Europe, hindering their capacity to scale operations to a larger extent[90,91]. This underscores persistent challenges within the fundamental framework for developing plant-based protein products. Inadequacies in infrastructure extend to outdated processing facilities, characterized by obsolete machinery and inefficient production lines. Critical gaps in processing and packaging plant-based proteins encompass limited storage capacities, along with outdated extraction methods[92,93] , insufficient processing techniques, and a lack of innovations in exploring new legume applications (**Figure 1**). Despite the emergence of promising techniques for protein extraction, aiming to preserve techno-functional properties, these approaches are still in the early stages of industrial application[187]. Their implementation in the EU faces obstacles related to legislative issues, including challenges with regulatory frameworks, compliance standards, and approval processes [94]. Navigating these legislative challenges involves negotiating complex regulations regarding food safety, labeling,

and ingredient approval[95]. Adapting existing regulations to accommodate innovative processes and ensuring that these new technologies meet established safety and quality standards may also present formidable challenges[94] .

While considerable exploration and innovation in novel processing technologies for plant-based protein have occurred, much of it remains at the research stage, with limited success in bringing these innovations to market[96]. This situation is especially notable as different legumes may require distinct protein extraction methods and associated equipment, some of which necessitate further research to address safety and appeal concerns related to anti-nutritional compounds[92,93]. **Figure 6** illustrates some of the techniques that exist and have improved the processing stage of the grain legumes value chain[96]. Despite these advancements, the scarcity of successful innovations constrains product diversification and market potential for legume-based products. This challenge is exemplified in the utilization of grain legume seeds, such as lupin, for their high-quality protein in diverse food products, which is well-recognized[2,16,97]. For instance, the presence of bitterness in lupin poses a notable challenge, necessitating advancements in breeding and processing techniques to mitigate its impact on taste[53,98,99].Lupin processing involves various stages, including cleaning, dehulling, and milling, with ongoing technological developments to enhance efficiency[7,100]. Despite predominantly engaging in grain legume processing, small enterprises encounter a technological gap, evidenced by outdated machinery and inefficient production lines[101,102,103]. Additionally, the selection of packaging materials for various legume-based products emerges as a critical factor influencing shelf life and sustainability, occasionally leading to adverse environmental effects[104,184]. Addressing these challenges in grain legume protein processing requires a holistic approach that spans breeding, processing innovation, and sustainable packaging practices.

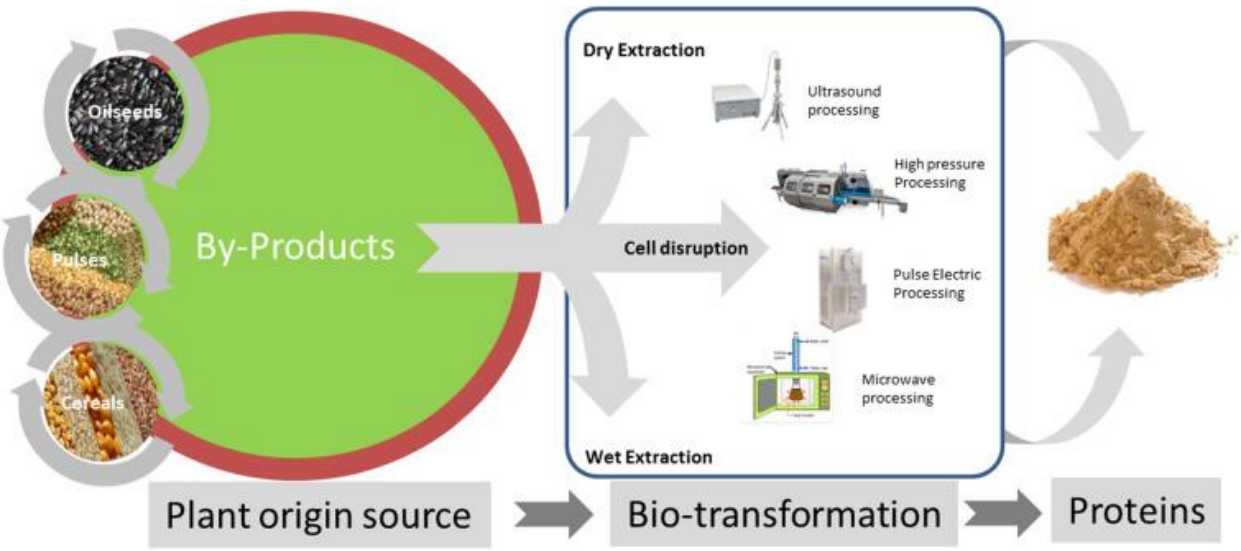


***Figure 6**: Eco-innovative technologies for protein extraction[96].*

While common processing challenges affect various legume crops, further specific limitations are notable in the processing of individual legumes. Pea protein, despite its growing popularity, encounters hurdles due to limited processing capacity, marked by a shortage of essential specialized facilities and equipment for efficient extraction, concentration, drying, quality control, hygienic processing, and storage/packaging[19,28,97]. Similarly, faba beans, renowned for their protein richness, face challenges stemming from limited processing capacity and a lack of sufficient large-scale facilities[19,80,105]. Potential remedies involve the development of advanced processing technologies[106] tailored to enhance the scalability and efficiency of faba bean processing, addressing the current

constraints in the production chain. Furthermore, chickpea processing confronts challenges, including the absence of standardized equipment hindering efficient dehulling, and a scarcity of knowledge affecting potential applications[107,108,109]. Likewise, lentil, despite being a good protein source, lack large-scale processing facilities[7,110,111]. Despite soybean's dominance in the realm of plant-based proteins, shared challenges persist across various legumes, encompassing the availability of processing facilities, quality considerations, and environmental impacts[92,93,112]. Addressing these specific limitations demands a comprehensive approach involving technological innovation, strategic investments, and the adoption of sustainable practices throughout the legume value chain, encompassing farmers and various stakeholders[7,11,113]. The recognition of these common hurdles emphasizes the need for collaborative efforts to fortify the overall sustainability and efficiency of plant-based protein processing across different legume crops.

3.4. Marketing and distribution

Navigating the marketing and distribution landscape within the value chain of plant-based proteins or protein crops in the EU involves considering various factors, including adherence to specific standards and certifications (**Figure 1**). In the plant-based space, compliance with standards such as those set by the European Vegetarian Union (EVU) or the European Vegetarian and Vegan Union (EVU) can be important[114]. These standards define the criteria for labeling products as vegetarian or vegan, ensuring transparency for consumers. In addition to such private standards, public standards, and associated regulations can be important. Public standards, often regulated by governmental bodies, aim to establish a baseline for quality and safety. Private standards, on the other hand, may vary across industries and organizations, adding complexity to the marketing landscape. Defining and meeting these standards become paramount in providing clarity to consumers, fostering trust, and facilitating the seamless distribution of plant-based products in the EU. Issues relating to use of terms such as “dairy”, “meat”, “burger”, “milk” are relevant in this context.

3.4.1. Certification and standardization

As with other value chains, certification and standardization play important roles in the plant-based protein value chain, with implementation varying across stages and regions[6,11,21]. Challenges and limitations in this process are not uniform, exhibiting differences by country and region[11,21,115]. In the European Union (EU), standards may differ from those in the United States, and variations can even exist within the EU due to different national certification bodies adhering to distinct rules set by the EU. While certification and standardization processes are crucial for ensuring transparency[6,116,117], navigating these processes in Europe may present challenges, as standards can vary between countries. Moreover, transparency issues in the certification and standardization process hinder the understanding of criteria met by products or how standards are enforced, posing challenges for consumers and businesses[115,118]. This opacity may contribute to a lock-in scenario, where a limited number of actors control the certification process, resulting in a deficit of accountability and trust[11,115]. Addressing these issues is vital for fostering transparency, ensuring adherence to standards, and building trust in the plant-based protein industry within the EU.

In the context of plant-based products, the certification and standardization process may exhibit a limited scope, often focusing on specific aspects such as food safety or organic standards[119,120]. This targeted approach creates gaps, leaving critical elements like social or environmental sustainability insufficiently addressed[121,116,122] —particularly crucial in the plant-based industry's commitment to holistic ethical and ecological considerations. Adding to the complexity, a lack of harmonization among

different certification and standardization schemes in Europe may lead to confusion and duplication, impacting both producers and buyers in the plant-based sector[11,113]. The enforcement of these standards can be weak or inconsistent, potentially allowing non-compliant plant-based products to enter the market or fostering a false sense of compliance[11,115]. Such gaps pose a risk, enabling non-compliant plant-based products to circulate freely or undermining the recognition and reward of compliant ones[11]. Additionally, the costs associated with certification and standardization may act as a barrier for small-scale plant-based producers or buyers in Europe, contributing to a scenario where only larger entities can bear the financial burden and comply with the standards[11,116,123].

3.4.2. Branding

Effective branding is a critical component in the marketing and distribution of plant-based proteins within the EU, serving to distinguish products, forge a unique brand identity, and communicate key values[11,116,124]. A robust brand not only aids in differentiation but also plays a pivotal role in building trust, particularly in a fiercely competitive market[116,124,125]. The evolving agricultural landscape, emphasizing organic and agroecological methods, has prompted a shift in value chain systems, with brands leveraging sustainability claims and product specificity to convey this transformation to consumers[126]. However, challenges persist, notably the lack of awareness, and indeed confusion, among European consumers regarding the benefits of plant-based proteins and their role in a healthy diet[11,92,127]. This awareness gap poses a hurdle for companies seeking to effectively communicate their brand's value proposition to consumers, emphasizing the need for targeted and informative branding strategies within the EU market.

The prevalence of traditional protein sources like meat and dairy products deeply embedded in European culture and cuisine poses a challenge for the widespread acceptance of plant-based protein products in the market[11,128,129]. The European market for plant-based protein products is notably fragmented, with numerous small and medium-sized players vying for market share, making it arduous for companies to establish distinct brand identities and product differentiation[101,102,103]. Moreover, regulatory hurdles in the EU, pertaining to the labeling and marketing of plant-based protein products, further complicate market dynamics[11,116,128]. Stringent regulations govern the use of terms like "meat" and "milk" for plant-based alternatives, challenging companies in effectively communicating the nature of their products to consumers[130,131]. For instance, the term 'protein-rich foods' is recommended as a more inclusive label for meat alternatives, acknowledging their diverse nutritional content and broader health benefits[132]. In the context of plant-based dairy alternatives, European regulations, specifically outlined by the Court of Justice of the European Union (CJ-EU) in 2017, restrict any mention resembling milk, cheese, yogurt, or similar terms on the labels of plant-based foods[191,192]. This regulatory landscape underscores the complexity companies face in accurately representing their products while complying with EU standards.

Overall, these lock-ins and gaps in the marketing of plant-based proteins in Europe can make it challenging for companies to establish a strong market presence, communicate their value proposition to consumers, and compete effectively in the market[11,124,125]. Companies need to work with stakeholders across the value chain to address these issues and educate consumers about the benefits of plant-based proteins[6,9,11]. They also need to develop innovative marketing strategies to differentiate their products from those of competitors and comply with regulatory requirements to effectively brand their products in the European market[11,116].

3.4.3. Transportation

Effective transportation is vital for the timely delivery and optimal condition of plant-based products, playing a pivotal role in maintaining product quality and satisfying customer expectations. A comprehensive 2018 report by the European Commission highlights transportation challenges as a potential bottleneck in the supply chain, particularly over extensive distances and involving numerous intermediaries[133]. Maintaining the quality of plant-based products, especially those with a limited shelf life, becomes notably challenging within the European context[134]. The report further emphasizes insufficient transportation infrastructure in specific regions of Europe, contributing to delays and inefficiencies in the transportation of plant-based proteins or protein crops[135,136]. These gaps underscore the need for targeted investments and strategic interventions to enhance transportation capabilities within the European plant-based protein supply chain. Addressing these challenges is crucial for ensuring the sustainable growth and efficiency of the plant-based protein industry in Europe, meeting the rising demand for plant-based products across the continent.

3.4.4. Logistics and inventory management

The intricate supply chain of plant-based proteins or protein crops in Europe involves a spectrum of activities, including transportation, warehousing, inventory management, packaging, and handling, necessitating meticulous planning and control of the movement of goods, services, and information[137,138]. This complexity is heightened by the involvement of multiple intermediaries, from farmers to processors to distributors, each with distinct processes and systems, posing challenges in logistics and inventory management[6,9,137]. To specifically address the challenges inherent in the plant-based industry, an imperative focus on improved inventory management is crucial (**Figure 1**).. Tailoring inventory management systems to the unique characteristics of plant-based products, marked by their perishable nature, is key to reducing waste, ensuring timely deliveries, and optimizing overall supply chain efficiency[133]. Strategic investments in technologies enhancing inventory visibility, demand forecasting, and coordination among supply chain partners play a pivotal role in reinforcing the supply chain for plant-based products[133]. Collaborative efforts and targeted investments are indispensable for overcoming identified lock-ins and gaps in the transportation of plant-based proteins or protein crops in Europe[133].

The seasonality in the production of plant-based proteins or protein crops introduces additional complexity, necessitating proactive measures to address challenges in inventory management[18,139]. Some plant-based protein products with a short shelf life require investments in refrigeration and storage technologies for shelf life extension[18,138]. Quality control emerges as a critical aspect, demanding investments in systems that ensure proper storage and transportation to meet expected standards[11,140]. Tackling these challenges comprehensively in Europe mandates investments in supply chain partnerships, storage facilities, and quality control systems specifically tailored to the nuances of plant-based products[11,137,138]. Emphasis on efficient processes is paramount to meeting consumer demand and ensuring the sustainability of the plant-based protein industry in Europe.

3.5. Sales & Retail

The growing market for plant-based protein products in Europe holds immense potential for retailers. However, challenges such as limited consumer awareness, uncertain preferences, pricing inconsistencies, and some consumer resistance to plant-based diets hinder the full realization of this

opportunity. Factors contributing to gaps in sales and retail of plant-based proteins include limited consumer awareness[93,141,142], uncertain preferences[93,118], and pricing inconsistencies[112,118], as well as some consumer apathy or resistance to plant-based diets, hinder the full realization of this opportunity in Europe[93,112,142] (**Figure 1**). These challenges manifest in various ways, with retailers struggling to customize product assortment and pricing strategies to diverse consumer preferences, resulting in disparities in product availability and affordability across different regions[118]. Furthermore, insufficient culinary expertise in the food service segment, combined with constraints in public procurement practices[143], limits menu variety and choice for consumers, impeding the broader adoption of plant-based options. Additionally, the lack of well-defined guidelines for fortifying nutrient gaps in plant-based proteins, coupled with sensory attributes that may not align with consumer expectations or meet specific market requirements, presents a substantial challenge[14,93,116]. To address this gap, considerations such as reducing the level of processing in some plant-based foods, emphasizing nutritional benefits, and expanding the value proposition beyond sustainability alone are suggested[93].

From a sales and retail perspective, plant-based proteins sourced from lupin, peas, faba bean, chickpea, lentil, and soybean are gaining traction in the European market. Lupin, valued for its high protein content and sustainability, faces challenges due to its bitter taste, but efforts to develop milder-tasting varieties indicate anticipated growth, especially as a soybean substitute[11,18] Peas, on the other hand, have witnessed increased popularity, yet concerns persist about their distinct earthy flavor, which can impact consumer acceptance[18,28,144]. The use of flavour or colour maskers or innovative processing technologies holds promise in addressing this challenge, potentially enhancing the marketability of pea-based products in the European landscape. Faba bean, still relatively unknown, struggles with market recognition, further complicated by supply chain and distribution limitations[2]. Chickpeas, despite being a staple in many cuisines, face a lack of consumer awareness in Europe, requiring effective marketing campaigns to highlight their nutritional benefits[145,146]. Competition from other legumes like lentil and beans, coupled with the unpredictability of supply due to weather conditions, presents additional challenges (7). Lentil confronts challenges in the market due to competition from cheaper imported alternatives, impacting the availability of domestic supply[11,85]. These legumes collectively grapple with supply chain and distribution issues, hindering their availability in retail outlets[11,85]. Soybean, while established as livestock feed, struggles to find a foothold as a human food source in Europe. Challenges in the supply chain and distribution further limit the availability of soybean-based products[11]. The higher producer price of soybean compared to other legumes emphasizes the need for strategic market positioning, for instance in the German market[18]. In summary, the European market for plant-based proteins is diverse, with each legume facing unique challenges. Insights from organizations like The Good Food Institute (GFI) highlight the importance of addressing supply chain complexities and enhancing consumer awareness for sustained growth in this evolving market[147].

Despite various initiatives promoting plant-based proteins, such as the Danish government's action plan incorporating green requirements in public food tenders and Ghent's "Thursday Veggie Day" as part of the Ghent en Garde initiative[148], challenges persist. Notwithstanding these efforts, a lack of skills and knowledge in this segment obstructs the broader adoption of plant-based options, and the limited promotional endeavors by retailers further hinder product visibility[38,142], creating a cycle where a lack of awareness and visibility perpetuates the challenges faced by the plant-based protein market. Addressing these issues demands collaborative efforts, targeted educational initiatives, and strategic marketing to enhance consumer understanding and cultivate a more supportive environment for plant-based protein products in the European market. Recognizing the

significance of these initiatives, it is crucial to emphasize the need for scaling and replicating these efforts for broader impact.

Given the challenges outlined, a deceleration or plateauing of sales is observed in the plant-based protein market. Some brands are prompted to withdraw due to insufficient demand and various market acceptance factors[149,195]. This trend of product withdrawal is influenced by factors such as unrealistically high growth expectations, adjustments in production capacity, and industry consolidation[150]. Furthermore, a decrease in financial backing and a reduction in significant business deals within the plant-based protein market are evident[151]. The decline in funding and the absence of substantial business transactions, often termed as "mega deals," may result in diverse effects on the market, including decreased investment, limited funds for research and development, and difficulties in securing crucial partnerships or acquisitions necessary for driving market growth[151]. In addition, the market for plant-based items is inherently subject to the unpredictable and volatile nature of consumer demand, posing challenges for companies along the value chain[1,8,11]. Sudden shifts in consumer preferences can present risks, potentially causing lock-ins when investments in specific plant-based ingredients do not align with these changes. This can result in challenges such as excess inventory and unused production capacity, impacting the overall market dynamics. This situation may contribute to a deceleration or stagnation in sales, potentially leading to brand withdrawals from the market due to financial constraints and inadequate support.

3.6. Value chain actors

The plant-based protein value chain involves various actors collaborating to deliver products from farms to consumers, encompassing farmers, input suppliers, processors, distributors, and retailers[5,6,8](**Figure 1**). Despite these actors potentially contributing to challenges and gaps, they also possess the capacity to address and mitigate these issues. Farmers, integral to the value chain as primary producers, face challenges such as inconsistent seed supply, unpredictable weather conditions impacting yield, and competition from imported alternatives, which can result in gaps in the supply chain[6,7,11]. For instance, European farmers relying on conventional crop varieties not optimized for protein content or yield may experience a lock-in, limiting profitability and hindering the development of improved varieties[7,11,152]. This can result in lower profits and limit the development of new and improved protein crop varieties[8,11]. Farmers may also contribute to gaps in the value chain when not adopting sustainable farming practices, including reducing the use of pesticides and fertilizers. Such practices, if not implemented, can actively contribute to a more resilient and sustainable plant-based protein industry in Europe[8,11,153].

Within the intricate framework of the plant-based protein value chain, input suppliers, encompassing crop breeders or seed suppliers[5,11,137], agribusiness companies, and equipment vendors for irrigation and harvest machines[11,69,154], play a pivotal role in providing farmers with essential resources such as seeds, fertilizers, pesticides, and other inputs necessary for crop production. However, unintentional actions by input suppliers can contribute to creating a lock-in within the value chain. This may occur when seed suppliers focus predominantly on conventional crop varieties, neglecting investment in research and development of new protein-rich varieties. The limited availability of innovative crops restricts choices for farmers, processors, and consumers, hindering the dynamic evolution of the value chain[8,11,137]. Additionally, input suppliers promoting specific crop varieties and inputs may reduce overall crop diversity, creating a lock-in situation where stakeholders become dependent on a narrow range of options[8,11]. Additionally, input suppliers may not provide

adequate information on best practices for seed selection and cultivation[7,8,11] and enough technical support to farmers, which can lead to suboptimal crop production[69,113,155].

Continuing along the plant-based protein value chain, processors play a pivotal role in converting protein crops into value-added products, including feed, ingredients, or consumer goods like soybean meal, tofu, and various protein products[11, 19,156]. However, processors might contribute to lock-ins within the value chain by relying on conventional processing methods that are not optimized for protein crops or by neglecting investments in innovative processing technologies capable of enhancing product quality and introducing new protein products[6,113,157]. This limitation can impede the availability of high-quality products in the market and diminish the competitiveness of the value chain[11,18,157]. Furthermore, processors may create gaps in the value chain by not establishing quality standards and traceability systems, negatively affecting the market reputation of protein crops[5,145,157]. It's essential to recognize that a lack of infrastructure for scaling up processes may also hinder the adoption of new technologies, as processors may face challenges transitioning from lab-scale to commercial-scale production.

In the advanced stages of the value chain, food manufacturers, exemplified by companies like "LikeMeat" and "Alpro," play a vital role in product development, marketing, and distribution[9,11,145]. These companies utilize diverse plant-based ingredients, such as soy, wheat, and pea protein, sourced from various suppliers, to create and distribute a range of products including meat alternatives, dairy alternatives, and protein bars[130,131]. Similarly, "Alpro," a global manufacturer of branded plant-based products, sources ingredients from diverse suppliers to produce and distribute items like milk alternatives, yogurts, and desserts, available in supermarkets and health food stores[130]. Notably, the influence of food manufacturers extends beyond these examples, encompassing a spectrum of players, including alternative meat companies receiving investments, traditional food companies diversifying into the plant-based space, and startups developing innovative products based on fermentation and other techniques[6,145]. This transformative trend, exemplified by the growing involvement of traditional meat companies, such as Danish Crown, in developing hybrid products, underscores the dynamic shifts in the plant-based protein landscape. Recognizing the diversity of actors in the industry is crucial for a nuanced understanding of its dynamics, where both traditional and alternative players shape the future of plant-based proteins.

In addition to the key players in the value chain, regulatory oversight, represented by regulators and inspectors, significantly contributes to the integrity and safety of the protein crop industry throughout Europe[115,113]. These officers, associated with food safety authorities at both the European and national levels, focus on enforcing regulations and standards to uphold the safe production, processing, and distribution of protein crops. Responsibilities include setting and enforcing guidelines related to the use of pesticides, fertilizers, and other inputs in crop production[158]. They conduct rigorous monitoring and testing to detect contaminants like heavy metals, pesticide residues, and mycotoxins, ensuring adherence to safety and quality standards[11]. Employing tools such as inspections, audits, and investigations, these officers contribute to identifying potential inefficiencies or gaps in the supply chain, such as storage issues, transportation challenges, or limited market access[11,115,157]. Moreover, they are crucial in recognizing technological or regulatory barriers that may hinder the adoption of best practices in crop production, processing, and distribution[18,113,157].

In navigating the complex dynamics of the plant-based protein value chain, influential brand owners like Vly in Germany, Alpro in Belgium, and Valsoia in Italy play a pivotal role in shaping supply chains for ingredients and devising effective marketing strategies, all while ensuring brand quality and

consistency[11,124]. However, this influence can give rise to lock-ins, with suppliers relying heavily on the brand owner for a significant portion of their revenue, limiting their flexibility in negotiating terms or exploring alternative markets[11,124]. Concurrently, brand owners may create gaps by exclusively sourcing ingredients, potentially leaving other producers without a market or causing imbalances in the supply chain[11,124]. For instance, a brand owner may stipulate specific soybean varieties or protein content levels, concentrating production in designated areas[11,124]. Additionally, brand owners wield considerable bargaining power, possibly resulting in an uneven distribution of profits among stakeholders[11,124]. This is evident when brand owners successfully negotiate lower prices for raw materials, impacting the profitability and sustainability of farmers or suppliers[11,124].

In the intricate network of the plant-based protein value chain, distributors emerge as a vital link, taking charge of the transportation and sale of finished products to retailers and consumers[5,157]. Their influence on the value chain is dual, as they play a crucial role in safeguarding product quality through investments in logistics infrastructure, including cold storage and transportation[18,157]. Distributors who prioritize these investments contribute positively to the efficiency of the value chain, preventing spoilage and maintaining product integrity[5,18,157]. However, a potential challenge arises when distributors neglect such investments, leading to compromised product quality and a subsequent loss of market value[18,157]. In addition to this, distributors lacking comprehensive market information may face difficulties in strategic decision-making, impacting product pricing and distribution. Collaboration with other value chain actors, such as producers and processors, is essential to address these challenges, ensuring that distributors play a constructive role in maintaining a seamless and effective protein crop value chain[6,7,157].

In the intricate web of the plant-based protein value chain, retailers and food service establishments, comprising grocery stores, supermarkets, restaurants, and cafes, stand as the final link between producers and consumers, holding a crucial role in shaping the dynamics of the industr[5,157,159]. Their influence extends beyond the transaction of finished products, affecting the overall efficiency and sustainability of the value chain. Gaps may emerge when these outlets fail to invest adequately in marketing that promotes plant-based products and educates consumers, hindering the broader adoption of sustainable practices[11,159,160]. Additionally, their role in ensuring transparent and traceable supply chains, through accurate product labeling and information provision, is pivotal. However, the lack of collaboration among retailers, food service establishments, and other value chain actors may hinder innovation and efficiency, potentially creating lock-ins and impeding the industry's competitiveness and adaptability to evolving market demands[5,11]. Therefore, fostering collaboration among all stakeholders becomes paramount for a resilient and sustainable plant-based protein value chain.

Consumer engagement is a decisive force in shaping the intricacies of the protein crop value chain in Europe, exerting influence over both potential lock-ins and gaps[1,8,11]. A lack of awareness among consumers regarding the benefits of plant-based products and the challenges associated with animal-based alternatives can lead to a market bias. This bias may create a scenario where plant-based companies encounter challenges in establishing their presence in a market largely dominated by conventional products[1,8,9]. Additionally, the higher cost often associated with plant-based alternatives, driven by factors like production costs and economies of scale, may impede the development of the market if consumers are unwilling to pay a premium for these products, impacting the overall economic viability of the industry[8,9,11]. Furthermore, consumer-specific taste preferences and quality expectations can present challenges, potentially obstructing the development of value chains for

companies specializing in certain ingredients. This scenario may unfold if consumers resist specific products due to undesirable taste or texture, leading to the creation of gaps in the value chain[112,116].

In addressing these challenges, it is essential for value chain actors to foster collaborative efforts, emphasizing research and development, infrastructure investment, and strategic marketing to enhance the efficiency and sustainability of the protein crop value chain in Europe[8,9,11]. Furthermore, understanding the influential role of consumer education and engagement is crucial for creating a resilient market for plant-based products, ensuring that consumers are well-informed and receptive to the benefits of sustainable and innovative protein sources[8,9,11]. This multifaceted approach is vital for overcoming the diverse factors contributing to lock-ins and gaps, paving the way for a more dynamic, responsive, and sustainable protein crop industry in Europe[8,9,11].

3.7. Institutional framework

The institutional framework, encompassing policymakers, government agencies, and certification organizations, along with informal institutions influencing social structures, plays a significant role in shaping the protein crop value chain and the dynamics of plant-based products in Europe[1,8,118]. However, the specific contribution of these institutions to the occurrence of lock-ins and gaps within the value chain may vary based on contextual factors and the nature of the crop or product under consideration. Government initiatives and policies aimed at fostering more sustainable food systems and reducing the environmental footprint of food production and consumption have been implemented, with specific dietary models that often include plant-based foods promoted for nutritional and health reasons (**Figure 1**). Despite these efforts, public policies encouraging a shift in consumption patterns may face challenges due to the current lack of widespread awareness among the public regarding the necessity to change their consumption habits to align with these policies. To promote societal economic and social development, various mechanisms, including incentives like subsidies and grants, regulations, and tools addressing social norms, have been employed. These mechanisms aim to bring about positive changes in economic structures, community well-being, and societal norms[161,162,163]. Evaluations of such interventions, including educational initiatives and positive reinforcements to encourage sustainable behaviours, have been undertaken to assess their effectiveness and their impact on the protein crop value chain in Europe, with a view to scaling and replicating them.

Policymakers face the challenge of balancing diverse priorities and interests when shaping decisions related to the value chain of protein crops or plant-based products, often requiring trade-offs in their choices[7,8,11]. Prioritizing economic growth over environmental sustainability or public health may lead to policies favouring the existing status quo and potentially hindering the growth of alternative protein markets[1,7,11]. Policymakers are also influenced by lobbying efforts from powerful stakeholders, including farmers' associations or meat industry lobbies. These external pressures could influence the level of support for the development and promotion of alternative proteins, without necessarily advocating for or against any particular option.

Government agencies overseeing agriculture, trade, health and consumer protection play a crucial role in shaping the landscape for both animal-based and plant-based products[7,9,11]. Policies and regulations set by these agencies may inadvertently favour the production of certain agricultural outputs and foods over others (**Figure 1**). For instance, subsidies supporting conventional farming practices or trade agreements prioritising animal-based products might restrict market opportunities for plant-based alternatives[7,8,11]. Furthermore, the extent and focus of government investment in

research and development for alternative proteins can significantly influence levels of innovation and the emergence of new plant-based products[1,7,11].

Certification organizations are pivotal in guaranteeing the quality and safety of plant-based products, yet their role may inadvertently contribute to lock-ins and gaps in the value chain[11,116,118]. In some instances, certification schemes that are prohibitively expensive or overly intricate may dissuade small-scale producers from entering the market, resulting in a restricted diversity of plant-based products available to consumers[11,116,118]. Hypothetically, certification organizations might establish specific criteria or testing methods tailored to the unique characteristics of plant-derived ingredients or production processes. If these standards are perceived as more stringent or less accommodating than those applied to animal-based products, plant-based producers may face additional challenges in obtaining certifications, creating an uneven playing field for alternative proteins[11]. The potential differences in criteria related to sourcing, processing, or the absence of certain ingredients commonly found in animal-based products could pose challenges for plant-based producers striving to meet certification requirements. It's important to note that these scenarios are illustrative, and the actual standards would depend on the specific certification organization and prevailing regulatory considerations.

Social Norms, encompassing cultures, beliefs, and attitudes cultivated within diverse societies give rise to specific patterns of social behaviour. This implies that individuals tend to align their actions with the perceived norms upheld by their families, friends, colleagues, and associates. Socially accepted standards shape the dynamics of interactions and relationships. Customs, traditions, and informal rules can have a substantial influence over consumers' purchasing decisions. A number of studies underscores the crucial role these informal institutions play in the transition toward plant-based protein consumption[142,164,165]. Effecting a shift in consumer patterns toward plant-based diets necessitates a concurrent transformation in people's attitudes.

In Europe, the institutional framework plays a pivotal role in both enabling and constraining the development of plant-based proteins, necessitating a comprehensive assessment of how these institutions contribute to lock-ins and gaps in the value chain for a more sustainable and diverse food system[7,11,116]. The Farm to Fork Strategy, a part of the European Green Deal, is a key initiative driving this transformation. The strategy aims to make food systems more sustainable, ensuring environmental, economic, and social sustainability throughout the entire food supply chain (**Figure 1**). This includes promoting a shift towards a more plant-based diet to mitigate the environmental impact of food production and consumption. Notably, European Union countries have introduced a sustainability label to indicate the environmental impact of food products, endorsing the consumption of local and organic food as part of the educational efforts to inform people about their consumption impact[166]. Governments, policymakers, the broader market, society, and individuals share the responsibility of addressing identified gaps. A diverse range of policy instruments is crucial to enhance plant-based production and consumption. This requires a coherent policy mix, ensuring effectiveness and clear signals of government intent. Relevant instruments encompass communication and promotion campaigns, public procurement, R&D funding for plant-based innovation, investment in agricultural extension services, harmonized tax rates, subsidies (e.g., carbon credits) to encourage legume cultivation, and the establishment of labeling and marketing standards for a level playing field. Additionally, altering individuals' perceptions, beliefs, and attitudes toward plant-based products is pivotal for driving this protein transition.

4. Acknowledgements

We thank the project partners and specifically Riccardo Calabrese (CONFAGRICOLTURA) and Claudio Carpineti (CONFAGRICOLTURA) for contributing to this work.

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6. Appendix

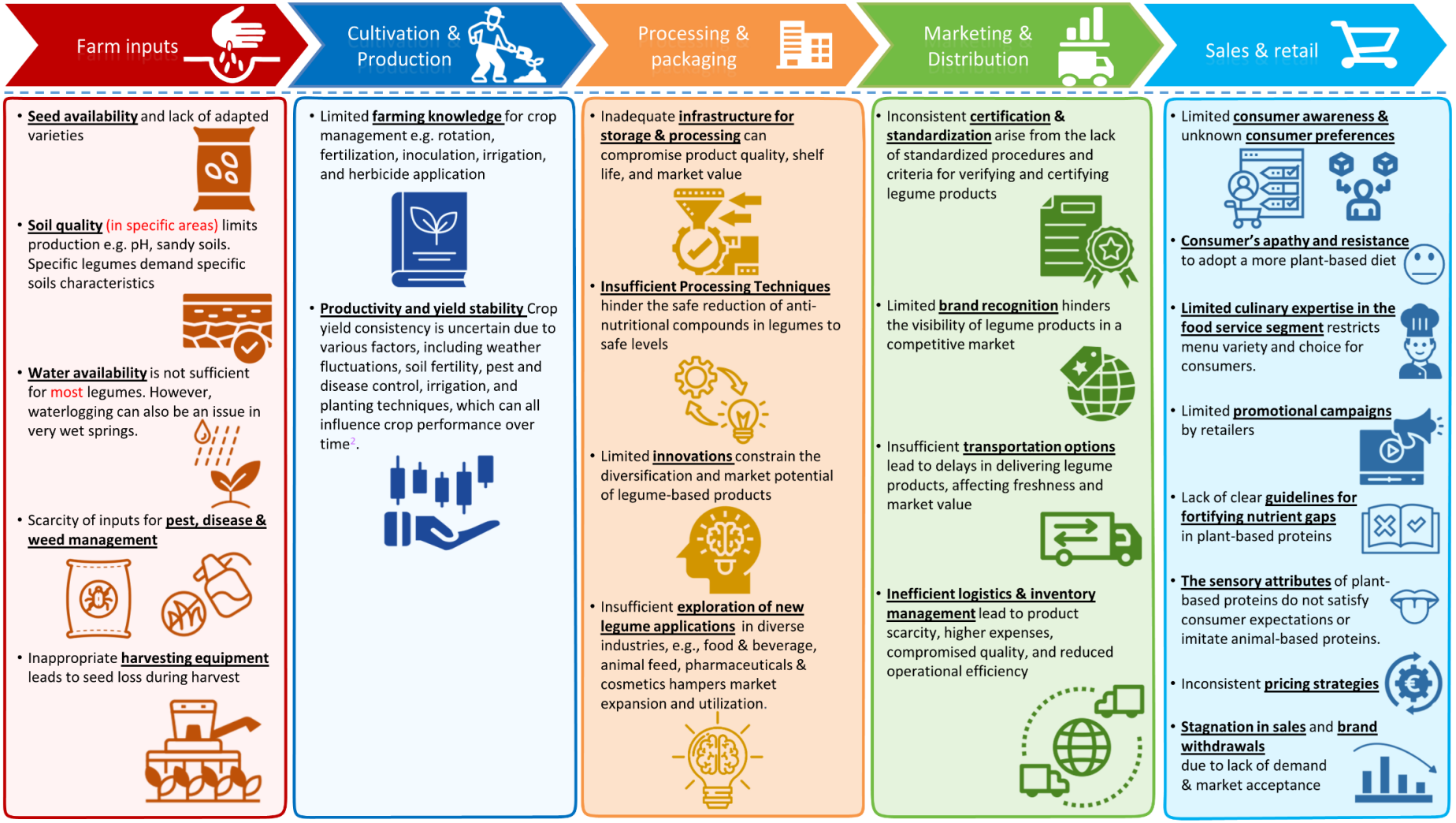

***Figure A1**: Infographic mapping gaps in protein crop value chains across Europe.*