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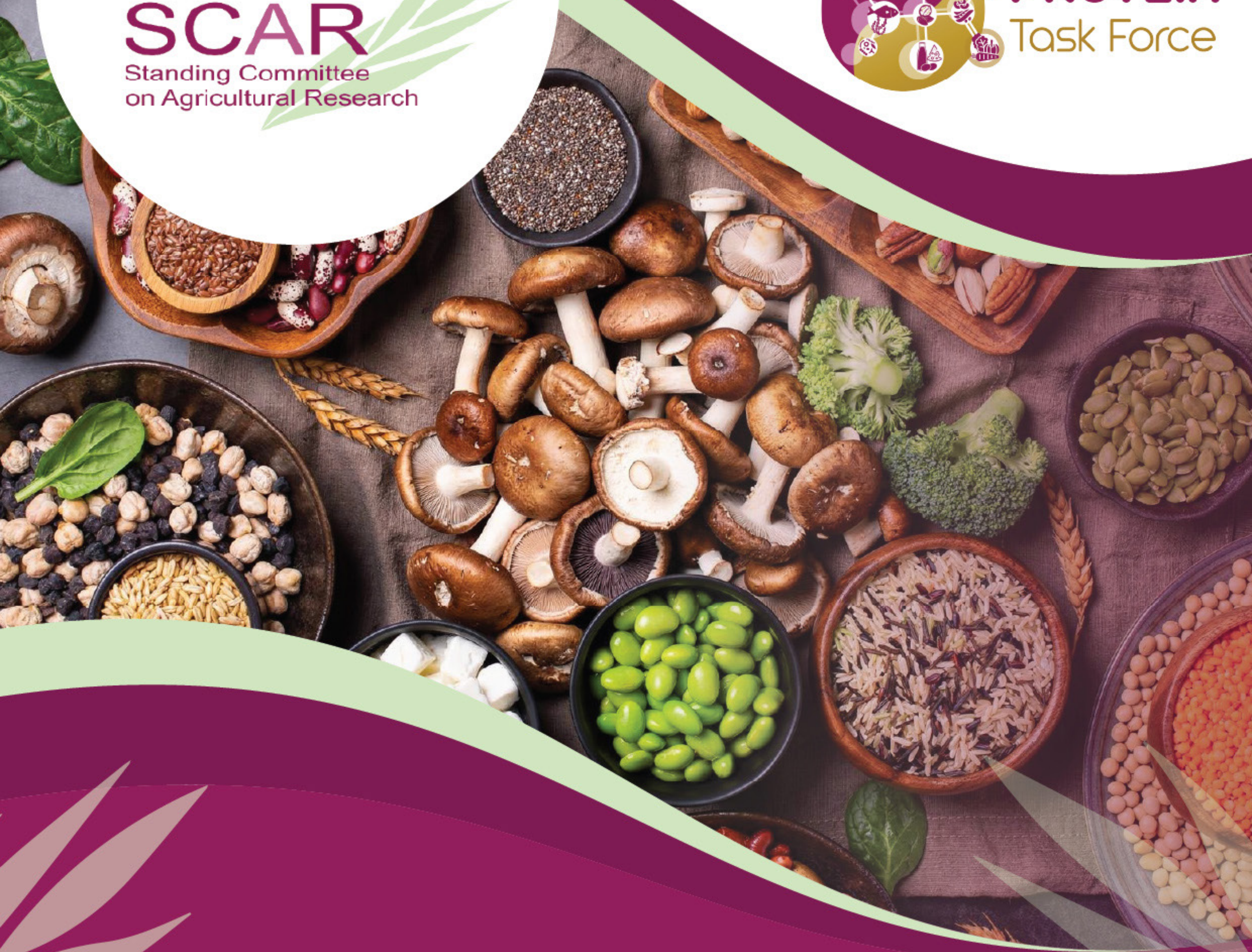

R&I FOR ALTERNATIVE PROTEIN SOURCES TOWARDS STRATEGIC AUTONOMY AND SUSTAINABILITY IN EU PROTEIN PRODUCTION

SCAR Protein TF   Policy Review and Analysis

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Disclaimer: The protein transition topic is inherently complex, cross-sectoral and highly multidisciplinary, encompassing biological, technological, environmental, economic and social dimensions. The reflections and recommendations presented in this document do not aim to offer an exclusive or binding treatment of the subject. Rather, they represent a collective work delivered by the SCAR Protein TF members, developed within the scope of their knowledge, capacities and available resources. There is room for further deep individual analysis on each specific protein source and protein value chain stage.

0. EXECUTIVE SUMMARY

Context & Background

Proteins are a cornerstone of the European Union (EU)'s food and feed systems, underpinning health, environmental sustainability and economic resilience. They are essential macronutrients for human and animal nutrition, yet the EU protein landscape is marked by structural vulnerabilities. Despite high overall availability, the EU remains heavily dependent on imports: currently, 66% of the EU's high-protein feed is imported, with a 96% for the soya bean meal. This dependency exposes the EU to global market volatility, geopolitical tensions and environmental sustainability issues. Domestic production of crude protein, estimated at 64 million tonnes in 2023–2024, is dominated by roughage and cereals, while protein-rich crops like legumes and oilseeds play a modest role. Consequently, the EU faces a persistent plant protein deficit, requiring annual imports of approximately 19 million tonnes to meet food, feed and industrial needs.

The livestock sector remains a pillar of the EU agricultural economy, shaping rural employment and land use, but its feed systems depend heavily on imported concentrates, creating systemic fragility. At the same time, European diets are characterised by high consumption of animal-based proteins (60%), with dairy, pork, poultry, beef and eggs dominating intake. Plant-based proteins, including pulses, account for only 2% of consumption, despite their nutritional and agronomic benefits.

The EU protein system, as part of the broader food system, faces interconnected challenges across supply and demand. On the supply side, constraints include limited cultivation of protein crops due to climatic conditions and lower profitability compared to cereals. Historical policy incentives have reinforced cereal-based farming systems, while gaps in processing infrastructure, product innovation and marketing hinder value chain development. Environmental pressures from intensive livestock production, such as Greenhouse Gas (GHG) emissions, nitrogen leaching and land degradation, compound these risks. On the demand side, unbalanced diets can lead to health issues, while healthier plant-based proteins remain under-consumed. Socio-economic factors, cultural preferences and established supply chains further shape consumption patterns, making behavioural change complex.

Despite these structural challenges, significant opportunities exist to transform the EU protein system. Increasing domestic cultivation of protein-rich crops such as soybeans, peas and lupins can reduce import dependency while improving soil health and biodiversity through crop rotation and nitrogen fixation. Policy instruments like the Common Agricultural Policy (CAP), combined with research, farmer training and improved market access, can accelerate this shift. Complementary strategies include promoting dietary transitions aligned with health and sustainability objectives through public campaigns, labelling, procurement policies and education. Advancing sustainable livestock systems that emphasise nutrient recycling, low-opportunity-cost feed sources and biodiversity-friendly practices can balance productivity with environmental goals. Feed efficiency technologies, including precision feeding and enzyme additives, offer further potential to reduce waste and emissions.

Alternative protein sources represent a critical frontier for both food and feed systems. Microbial proteins, insects, algae and cultured meat offer pathways to reduce land use, emission and water consumption, though they require technological maturation, regulatory frameworks and consumer acceptance. By 2035, alternative proteins could capture 11-22% of the global protein market. Algae show strong potential to replace soy in feed, insect-based protein is projected to reach 3.1 million tonnes by 2030 and microbial fermentation could contribute 22 million tonnes globally by 2035. Cultured meat, however, is expected to remain a niche contributor through mid-century. Mainstreaming these alternatives will require strategic actions such as aligning initiatives with national commitments, achieving price parity, nudging behavioural change, accelerating R&I and engaging food and health professionals to build trust and literacy.

Consumers are central to this transition. While awareness of sustainability and health issues is growing, adoption of alternative proteins remains limited due to concerns over taste, price, familiarity and perceived "naturalness." Clear labelling, food literacy initiatives and accessible pricing are essential to overcome these barriers. Public education, school meal programmes featuring plant proteins and transparent communication can foster acceptance. At the same time, consumers can drive change by supporting local protein sources, exploring plant-based meals and demanding sustainability from producers.

Achieving a sustainable and resilient EU protein system requires a systemic approach that integrates supply- and demand-side measures, balances economic and environmental interests and aligns short-term actions with long-term goals. Coordinated policy reform, investment in research and infrastructure, particularly in processing and marketing and active consumer engagement are critical. If supported by integrated strategies and robust R&I ecosystems, the EU can reduce its vulnerability to external shocks, lower GHG emissions and nitrogen pollution, enhance food security and position itself as a global leader in the transition toward climate-smart, competitive and socially acceptable protein systems.

Policy Context

Sustainable protein production and consumption are key drivers for achieving global sustainability goals. In the EU, protein supply and demand have become strategic issues across agriculture, trade, health, environment and research policies. Recent initiatives aim to reduce import dependency, diversify protein sources and promote sustainable diets.

The *European Green Deal* and *Farm to Fork Strategy* introduced a systemic approach integrating agricultural and nutritional objectives, encouraging sustainable farming and alternative proteins. The CAP now supports protein crop cultivation through targeted measures, while a legal framework for a sustainable food system is still pending. The EC's 2025 Vision for Agriculture and Food emphasise expanding and diversifying EU protein production to strengthen food sovereignty and resilience. A forthcoming EU-wide strategy will address the entire protein value chain, aiming for self-sufficiency, sustainability and competitiveness.

Key policies challenges identified by the SCAR Protein TF are:

I. Integrating the entire value chain into the development of holistic strategies and the corresponding mainstreaming into action plans and policy measures.

II. Cross-sectoral alignment of policies within a holistic, coherent policy framework by using a food system and policy mix approach.

III. Addressing innovation, scaling up, *exnovation* of existing structures and measures that no longer meet objectives, as well as managing potential trade-offs within a consistent policy mix.

Scope & Objective

European protein transition depends on strong R&I strategies to develop alternative sources, boost local production and ensure societal uptake. It is critical for bridging innovation, policy and consumption, enabling a climate-resilient and nutritionally balanced protein future aligned with EU goals on sustainability, health and food security.

In this context, the SCAR Protein Task Force promotes a coexistence and diversification approach, combining conventional and novel proteins to reduce dependency, enhance resilience and respect regional and cultural diversity. This inclusive strategy supports gradual dietary shifts, consumer acceptance and sustainability goals, while anticipating impacts such as waste management. Ultimately, coexistence ensures flexibility and social acceptability, aligning innovation with tradition and EU priorities on climate neutrality and food sovereignty.

The objective of this document is to explore how European R&I can drive protein diversification, sustainability and strategic autonomy across the EU food system. It aims to:

- Reviewing current protein production and consumption trends in Europe.
- Conducting a State-of-the-Art (SoA) analysis of R&I activities on alternative proteins.
- Mapping challenges and opportunities along the protein value chain.
- Proposing strategic actions and recommendations to strengthen R&I in alignment with EU sustainability and autonomy objectives.

The methodology applied in this document combines a SoA review with an in-house analysis and reflection, leveraging the expertise of the SCAR Protein Task Force together with insights from a Portfolio Analysis (PA) of EU-funded projects. Together, these approaches aim to provide a robust foundation for actionable recommendations and strategic directions to guide future R&I agendas toward a more autonomous, sustainable and resilient European protein system.

State of the Art on R&I for alternative Protein sources

Conventional protein sources	Livestock-based	Meat
		Fish
		Dairy
	Plant-based	Pulses
		Cereals and pseudocereals
		Oilseeds
		Nuts
Alternative protein sources	Plant	
	Micro-organisms	
	Insects	
	Cultured meat	
	Marine feed stocks	
	By-products from bio-economy (Biotechnology, precision fermentation)	

Figure A. Protein Sources

Crop-Based Protein Sources (including pulses, climate-resilient cereals, pseudocereals and oilseeds), offer multiple benefits for European agriculture and nutrition. These species contribute to agroecological diversification, nitrogen fixation and soil health, while enabling cultivation on marginal lands with lower input requirements. Despite these alternative crops advantages, systemic barriers persist. Agronomic constraints include susceptibility to heat stress, fungal contamination and limited genetic diversity in crops. Processing challenges hinder industrial uptake: sorghum suffers from poor milling efficiency; pseudocereals require complex washing and drying to remove saponins; and oilseed biorefineries often rely on solvent extraction methods that compromise protein functionality and sustainability. Pulse protein isolation traditionally depends on wet fractionation, which is resource-intensive, while dry fractionation offers a more sustainable alternative with lower purity. Safety concerns, such as mycotoxin contamination in cereals and allergenic compounds in oilseeds, require harmonised mitigation strategies. Consumer acceptance remains uneven, influenced by sensory attributes, cultural perceptions and limited familiarity with crops like millet or sorghum. Nevertheless, growing demand for plant-based diets and valorisation of side streams (e.g., oilseed cakes) create opportunities for integration into meat substitutes, bakery and dairy alternatives.

Non-Crop Protein Sources (including algae, insects, microbial fermentation products and cultured meat) represent a rapidly expanding segment with transformative potential for Europe's protein landscape. These sources combine high protein density and essential amino acids with additional nutritional benefits. Production trends indicate strong momentum. However, scale-up and cost reduction are critical priorities across all sectors, requiring investment in infrastructure and process innovation. Safety considerations for this alternative protein sources are central under EU novel food regulations. Consumer acceptance varies widely and strategies to improve adoption include hybrid products, competitive pricing and targeted education campaigns. Integrating these sources into circular systems, such as insect upcycling of food waste or microbial fermentation using industrial gases, can further enhance resource efficiency and resilience.

Both crop-based and non-crop protein sources are indispensable for achieving EU's strategic objectives on protein diversification, climate adaptation and food system resilience. Realising this potential requires coordinated R&I strategies that address breeding for improved traits, development of low-impact processing technologies, safety assurance and consumer engagement. Policy frameworks must incentivise innovation, infrastructure investment and multi-actor collaboration across value chains.

In parallel with this SoA, a **Portfolio Analysis (PA) of projects** has been carried out to identify EU funded R&I projects (in progress or completed within the last 5 years) in the scope of this work and highlight knowledge gaps, overlaps and thereby outlining the future needs. Key projects were examined, covering the entire value chain from primary production to product prototyping, with most focusing on process optimisation and scalability, while others addressed consumer trust and market adoption. Common challenges identified in the PA include:

- Scaling up and achieving cost competitiveness due to high energy and processing costs.
- Regulatory bottlenecks under EU Novel Foods rules.
- Limited consumer acceptance and sensory issues.
- Fragmented supply chains and insufficient funding for continuation and feed trials.

Most projects operate at Technology Readiness Level (TRL) 4–7, highlighting the need for more fundamental research to address technical and systemic barriers. PA recommendations emphasise harmonised regulation, collaborative platforms, shared data resources, consumer education and multi-actor partnerships.

Mapping the Protein Value Chain: A Framework for Action

Across Europe, research on protein diversification increasingly adopts food system and transdisciplinary perspectives, in line with the Food 2030 vision for sustainable, healthy and resilient food systems. Yet, true scientific integration remains limited, with collaboration often confined to the application level. To structure the analysis carried out by the SCAR Protein Task Force, the protein value chain has been mapped as a guiding framework for identifying key research gaps and disciplinary interfaces critical, as illustrated below, to advancing sustainable and diversified protein systems.

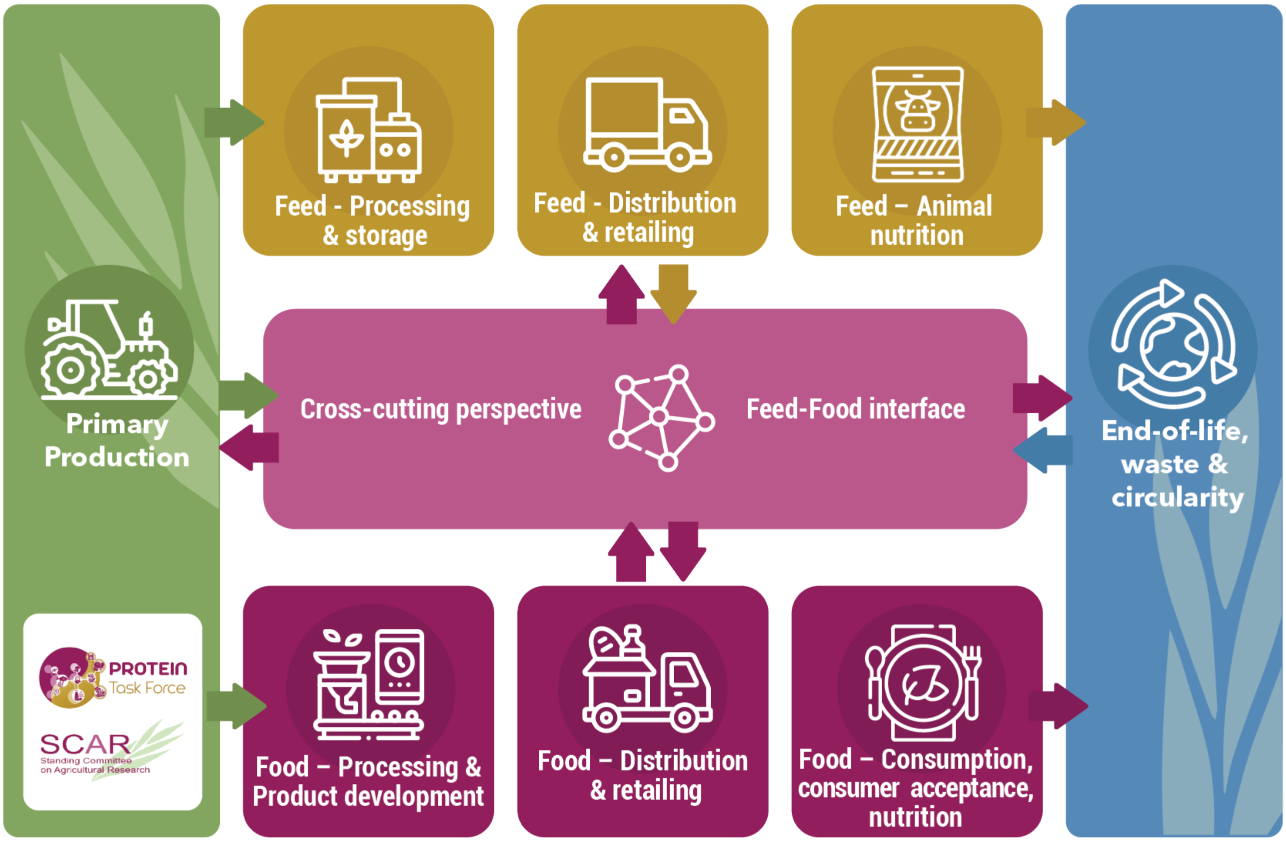

Figure B. Protein Value Chain approach taken by the SCAR Protein TF for analysis of the alternative protein sources towards strategic autonomy and sustainability in EU

Primary production shapes the availability, nutritional quality and environmental footprint of protein resources. Diversifying crops, such as legumes, pseudo-cereals, drought-tolerant cereals and oilseeds, offers agronomic and ecological benefits. Legumes, in particular, fix nitrogen, reducing fertiliser dependence and improving soil health and biodiversity. Crop rotations incorporating these species enhance resilience and agroecological practices. However, large-scale adoption remains limited due to low breeding investment, unstable yields and insufficient attention to traits like nutritional quality and processability. Agronomic knowledge gaps and lack of region-specific guidelines further hinder uptake. Advances in agroclimatic modelling and data analytics improve spatial planning, but fragmented performance data restrict predictive modelling and policy design. Stronger EU observatories and interoperable data infrastructures is essential.

Feed Value Chain is critical for livestock productivity and sustainability. Alternative protein sources, such as insect-derived proteins and agro-industrial by-products, can reduce import dependency and support circularity. Processing innovations, including fractionation, fermentation and lipid extraction, improve digestibility and palatability, but modular, low-cost technologies are needed for SMEs. Anti-nutritional factors must be mitigated through breeding and processing strategies, while robust quality control ensures safety and traceability. Efficient distribution and short supply chains minimise waste, supported by digital platforms for by-product matching. Insect farming exemplifies circularity by converting residues into feed and producing frass as organic fertiliser. Animal nutrition faces challenges of variability and knowledge gaps on digestibility and species-specific responses. Precision feeding and modelling tools will be key to integrating novel feedstuffs without compromising performance.

Food Value Chain determines the nutritional, functional and sensory properties of protein-rich foods. Operations such as fractionation, fermentation and extrusion influence digestibility, amino acid bioavailability and texture. Despite technological progress, EU protein foods rely heavily on soy and pea, while underutilised crops face processability challenges, raw-material heterogeneity and fragmented supply chains. Differences in biochemical composition and microstructure translate into inconsistent milling, extraction and structuring performance, which remain insufficiently characterised across crops and scales. High-throughput analytics, predictive modelling and adaptive processing approaches are therefore needed to manage variability and enable data-driven process optimisation. While dry, wet and hybrid fractionation routes offer contrasting trade-offs between yield, purity and resource intensity, integrated sustainability assessments remain necessary to guide design-for-sustainability in processing choices. Distribution and retailing strongly influence consumer exposure, with public procurement acting as a lever for sustainable protein adoption. Digitalisation through blockchain and value-chain simulations can enhance transparency and efficiency. Consumer acceptance remains a bottleneck due to sensory limitations, cultural norms and perceptions of “ultra-processing.” Nutritional concerns and allergenicity risks must be addressed through standardised assessment frameworks.

End-of-chain stages are vital for resource efficiency and climate goals. Closing nutrient loops through manure processing and biorefinery platforms can recover resources and reduce emissions. Technological innovations in enzymatic and microbial valorisation enable conversion of side streams into high-value ingredients, but scaling demands robust safety and traceability frameworks. Multi-actor demonstration hubs are essential for testing cascading pathways and governance models. Shared biorefinery platforms should prioritise food applications while valorising residues into feed, fertilisers or biomaterials, reinforcing regional autonomy and sustainability.

Effective protein transitions require a **Cross-Cutting approach** with systemic integration across the entire value chain. Many challenges, such as quality standardisation, supply stability, traceability and sustainability metrics, are cross-cutting. Opportunities arise from complementarities between feed and food uses, requiring integrated R&I frameworks linking breeding, agronomy, processing, nutrition and health. Shared territorial infrastructures and harmonised sustainability metrics will enable transparent governance and evidence-based policy. Circular and cascading biorefinery pathways must be guided by multi-criteria life-cycle assessments, ensuring alignment with food safety regulations. Governance models that foster trust, fair value distribution and coordinated investments, through interbranch agreements and regional partnerships, are essential to accelerate systemic change.

Based on the above value chain stages, the SCAR Protein TF has analysed the respective challenges and opportunities to break them down and from there, derive a series of potential actions. The table below presents one of the main outcomes of this work. It consolidates the proposed actions and translates them into a structured set of recommendations organised along the protein value chain (further elaborated in Section 4):

Primary Production

- Invest in multi-criteria breeding programes for yield stability, resilience, nutrition, and processability
- Develop predictive quality markers and high-throughput screening tools for raw material allocation
- Scale agroecological innovation through LLs, demo farms, and advisory networks with digital tools
- Strengthen EU observatories and interoperable data platforms for agronomic & market data integration

Feed Value Chain

- Deploy modular, low-cost processing technologies to valorise regional feedstocks and reduce imports
- Reduce anti-nutritional factors through combined breeding and processing strategies
- Create open-access nutritional databases and precision ration tools for diet optimisation
- Fund systematic multi-species feed trials to validate performance and health impacts
- Align feed innovation with One Health and climate-smart agriculture frameworks

Food Value Chain

- Advance predictive research on structure–function–nutrition relationships for better quality
- Invest in territorial processing hubs and pilot plants to scale protein innovations
- Harmonise EU labelling and regulatory frameworks with nutritional and environmental indicators
- Support culinary innovation and partnerships with chefs and food-service professionals
- Develop harmonised allergenicity assessment frameworks for emerging proteins

Circularity & End-of-Chain

- Apply a use-priority hierarchy (food > feed > non-nutritional uses) for biomass valorisation
- Develop low-energy, low-emission biorefinery technologies for cascading uses of co-products
- Advance enzymatic, microbial, and fermentation-based processes for side-stream valorisation
- Establish territorial demonstration hubs to test cascading pathways and governance models
- Integrate multi-criteria sustainability assessments into funding and regulatory frameworks

Cross-Cutting Priorities

- Create interoperable EU data infrastructures linking agronomic, processing & environmental datasets
- Standardise sustainability indicators across feed and food chains for transparent monitoring
- Design multi-level governance models to ensure fair value distribution and reduce transaction costs
- Embed protein diversification targets in CAP, rural development, and climate strategies
- Establish policy labs and living labs to co-design regulatory reforms and institutional arrangements

Figure C. Summary of the potential actions suggested for R&I for alternative protein sources towards strategic autonomy and sustainability in EU protein production along the protein value chain

1. CONTEXT & BACKGROUND

1.1. Protein Production and Consumption Scenario in Europe

THE RELEVANCE OF PROTEINS FOR FOOD AND FEED

Proteins play a **central role in the EU's food and feed systems**, with significant implications for health, the environment and economic sustainability. They are essential macronutrients necessary for health, growth and bodily functions in humans and animals alike and they play a vital role in both human and livestock nutrition. While most human protein intake in Europe currently comes from animal-based sources such as meat, dairy and eggs, there is a growing trend towards plant-based diets, reflecting evolving health and sustainability concerns [1–3].

EU protein supply is **heavily reliant on high-quality imports** from a limited number of origins [4]. This import dependency exposes the EU to various vulnerabilities, including global market volatility, evolution of trade policies of key global players, geopolitical instabilities, supply chain disruptions (as recently highlighted by the COVID-19 pandemic and the geopolitical tensions following the Russian invasion of Ukraine) climate-related challenges and environmental impacts abroad, such as deforestation and biodiversity loss in producer countries[5–7]. These challenges underscore the importance of proteins not only for nutrition but also for broader issues related to European food security, environmental sustainability, economic resilience and social stability [5,8].

These measures are seen as **key to reduce import dependency, enhancing food system resilience and mitigating environmental impacts**. Although these objectives have long been part of EU policy frameworks, recent global events have intensified the urgency to implement them effectively and comprehensively.

Addressing the challenges associated with protein supply and demand requires **integrated actions** that promote both sustainable production and consumption patterns across the continent[4,9].

PROTEIN SUPPLY & DEMAND IN THE EU

Current Scenario: Protein Production and Consumption in the EU

Between 2010 and 2023, Europe experienced a modest increase in average protein supply, growing by 4%, below the global average of 9%. Despite this slower growth, Europe had the highest protein supply in 2023, reaching **113 grams per person per day**, nearly double that of e.g. Africa, whereas the EFSA recommends intake for adults is 0.83 g per kg of body weight per day. This high level is largely due to the greater availability of animal-sourced proteins, which made up around 60% of total protein intake in Europe, similar to the Americas. In contrast, regions like Africa and Asia rely predominantly on plant-based proteins. These disparities highlight Europe's relatively high consumption of animal protein and its implications for sustainability and dietary transitions [10,11].

In the 2023-2024 period, the EU's arable crop sector generated approximately **64 million tonnes of crude protein**, with 46% derived from roughage (grass and silage), followed by 43% from cereals and 10 % from protein-rich crops (rapeseed, soya beans and dry pulses). Among oilseeds, rapeseed stands out as the primary protein-rich crop, while dry pulses contribute only 1.1 million tonnes, reflecting the still modest role of legumes in European agriculture [12,13].

Despite these levels of domestic production, the EU faces a long-standing plant protein deficit, needing the **annual import of approximately 19 million tonnes of crude protein** to satisfy the demands of food, feed and industrial sectors. Soybean products, especially soybean meal, constitute the bulk of these imports, which are heavily relied upon for feeding pigs and poultry. Currently, 66% of the EU's high-protein feed is imported and alarmingly, 96% of its soya bean meal (the EU's primary high-protein feed) comes from outside, raising significant concerns about the EU's dependence on external markets, vulnerability to global market volatility and contributions to environmental issues in exporting regions [14–16].

Human diets in the EU are **still dominated by animal-based proteins** (55-60 %), with dairy products, pig meat, poultry, beef and eggs comprising the largest shares. Between 2010 and 2021, animal protein consumption increased by 6%, while plant protein intake fell by 2% [17,18]. Pulses, despite their nutritional and agronomic benefits, still account for only 2% of plant-based protein intake [19]. This current dominance of animal protein in EU is not expected to change by 2035. An aging EU population is expected to keep the protein intake slightly higher, with a growing preference for dairy products, fish and poultry. While pulses are expected to grow the most, they could continue to contribute relatively little to the overall protein intake [20].

Then, the livestock sector remains a pillar of the EU's agricultural economy, shaping rural employment and land use. The sources of protein used in animal feed are both non-edible (such as grass) and edible for humans (mostly grains, including cereals and pulses). Based on EC 2024 data, **feed demand in the EU is stable at around 71 million tonnes in crude protein annually**, with 41% derived from roughage, 23% from crops (cereals, oilseeds, pulses), 33% from co-products and 3% from non-plant sources. High-protein concentrates represent 30% of the total, largely for pigs and poultry. However, as mentioned, 66% of these high-protein concentrates are imported, underscoring the structural vulnerability of the EU's feed system [12,21].

EU self-sufficiency for all sources of protein is expected to be at 75%. The EU remains fully sufficient in roughage and it is still the main source of feed protein. The share of all oilseed meals represents 27% of total feed protein use in the EU and the share of cereals represents 21%. However, for oilseeds meals, the EU only produces 27% of what it needs to feed its livestock sector [22].

Looking ahead, projections to 2050 anticipate divergent trends between the global and EU protein landscapes. **Globally, protein production is set to rise significantly**, driven by population growth and higher meat demand, particularly from pigs and poultry. By contrast, the EU medium-term outlook for agricultural markets up to 2035 identifies several factors that may contribute to a reversal of the past patterns, with a decreasing trend in EU meat consumption, prices, changing consumer preferences, health awareness and concerns about sustainability and animal welfare [7,15].

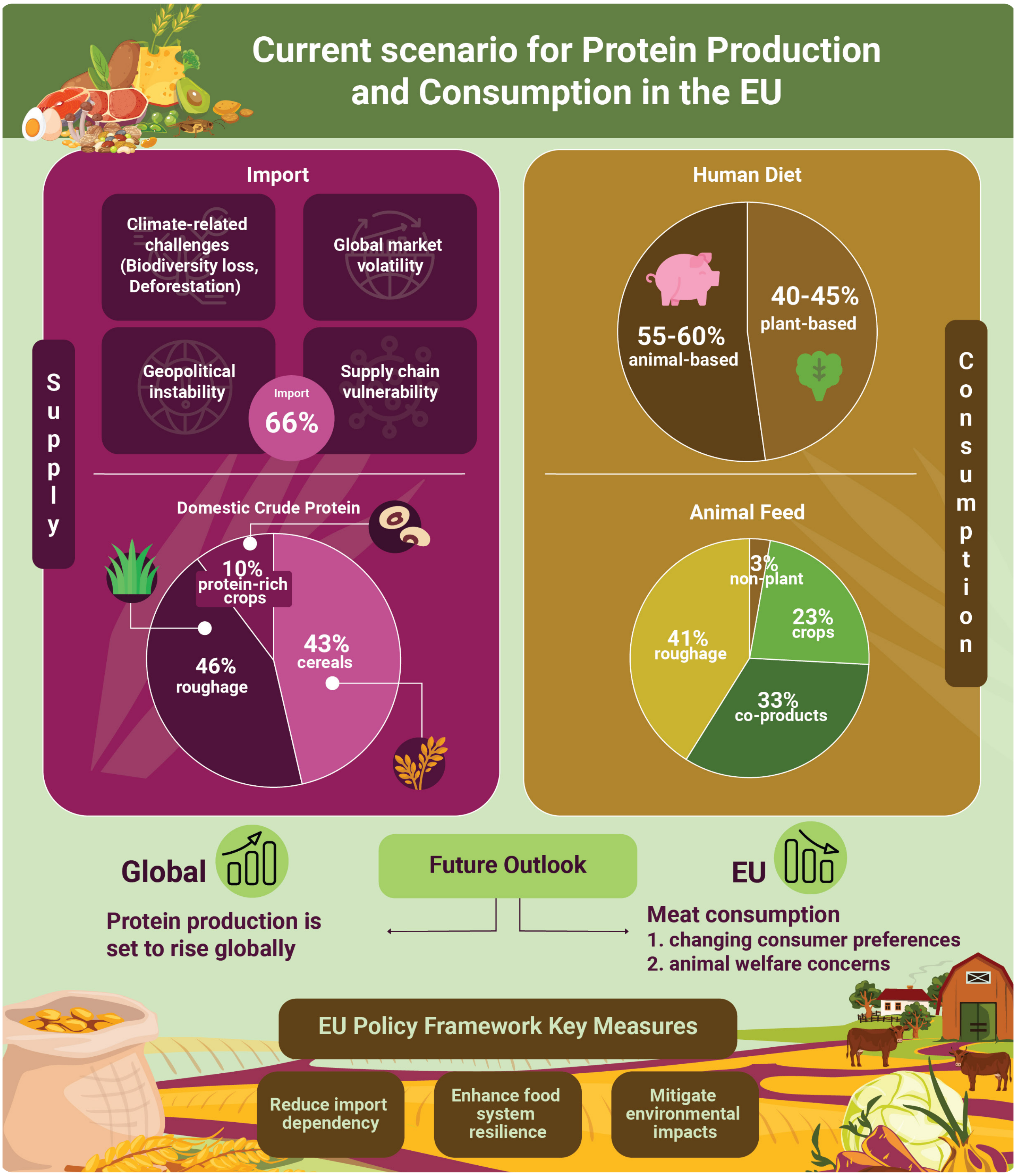

Figure 1. Current scenario for Protein Production and Consumption in the EU

Supply-Demand Challenges

The EU's protein system is shaped by several **interconnected challenges** across the supply and demand spectrum. At the supply level, a core issue is the region's dependence on imported high-protein feed ingredients, especially soybean meal. This dependence (concentrated on a few global suppliers) exposes the EU to external shocks, including trade disruptions, price volatility, geopolitical tensions and sustainability risks such as deforestation, soil degradation and biodiversity loss in exporting countries [6,8,15].

Within the EU, production of protein crops like soybeans, peas andlupins remains limited due to climatic constraints, lower profitability compared to cereals and GMO regulations [21,23]. The dominance of cereal-based farming systems, encouraged historically by EU agricultural policies, further **restricts diversification into protein-rich crops**. Additionally, regional disparities in agronomic knowledge, pest management and yields hinder efforts to scale legume cultivation [24].

There are also **significant value chain gaps**: outdated or unsuitable processing infrastructure, limited product innovation and marketing challenges such as lack of certification schemes, inconsistent pricing and low consumer awareness or acceptance of plant-based proteins [3,23].

Environmentally, intensive livestock production leads to substantial Greenhouse Gas (GHG) emissions, nitrogen leaching and land degradation. In regions with concentrated livestock farming, manure surpluses compromise soil and water quality. Furthermore, **feed-to-food conversion efficiency remains often low**, with only a fraction of feed protein ultimately consumed by humans as edible protein [7,25].

From the demand side, EU **diets are unbalanced**, with high levels of red and processed meat consumption linked to chronic diseases such as heart disease, obesity and cancer. At the same time, healthier plant-based proteins (including legumes, nuts and whole grains) are under-consumed, perpetuating both health disparities and environmental inefficiencies [17,18].

Supply-Demand Opportunities

Despite these structural and systemic challenges, the **EU has significant opportunities to transition** to a more sustainable and resilient protein system.

A major opportunity lies in **increasing domestic cultivation of protein-rich crops**, such as soybeans, peas and lupins. These crops not only reduce import dependency but also support soil health, biodiversity and climate resilience through crop rotation and nitrogen fixation [19,23]. Enhanced support through the Common Agricultural Policy (CAP) can incentivise farmers to grow these crops, especially if backed by research, training and market access [24].

Another strategic approach is **promoting dietary shifts** aligned with both health and environmental objectives. Public campaigns, food environment nudges (e.g., labeling and procurement) and education/literacy can help steer consumption patterns toward plant-based proteins, contributing to better public health outcomes and lower environmental impacts [18,26].

The **development of sustainable livestock systems** also holds promise. Systems that emphasise nutrient recycling, low-opportunity-cost feed sources and biodiversity-friendly practices can balance productivity with sustainability. In parallel, feed efficiency technologies, including precision feeding, enzyme additives and smart nutrient formulations, can reduce waste, improve resource use and cut GHG emissions [7,21].

Without changes in food systems, agriculture and food production will face excessive pressure, with unavoidable consequences for the environment and human health[27]. Moreover, **alternative protein sources are emerging as complementary solutions** to both food and feed needs. Insects, algae, microbial fermentation and cultured meat represent innovative protein avenues that can reduce land use, emissions and water consumption. However, these alternatives still require technological maturation, regulatory frameworks and greater consumer acceptance [28].

Realising these opportunities requires a **coordinated and systemic transformation**. Policy reform must align agricultural, environmental and trade objectives. Investments in research, innovation and infrastructure (particularly in processing and marketing of plant-based and alternative proteins) are needed to unlock value chain potential. Consumer engagement, through awareness campaigns, price incentives and trust-building in new food technologies, is also vital. Lastly, land-use strategies must balance food production, biodiversity conservation and climate goals in an integrated way [4,9].

A diverse, sustainable and resilient protein system would help **reduce the EU's vulnerability** to external supply shocks, minimise environmental damage, promote healthier diets and support strategic priorities like climate neutrality, food security and rural development. Modelling indicates that joint action on both supply and demand fronts can yield substantial benefits, including reduced GHG emissions, lower nitrogen pollution and greater food system stability [7,26].

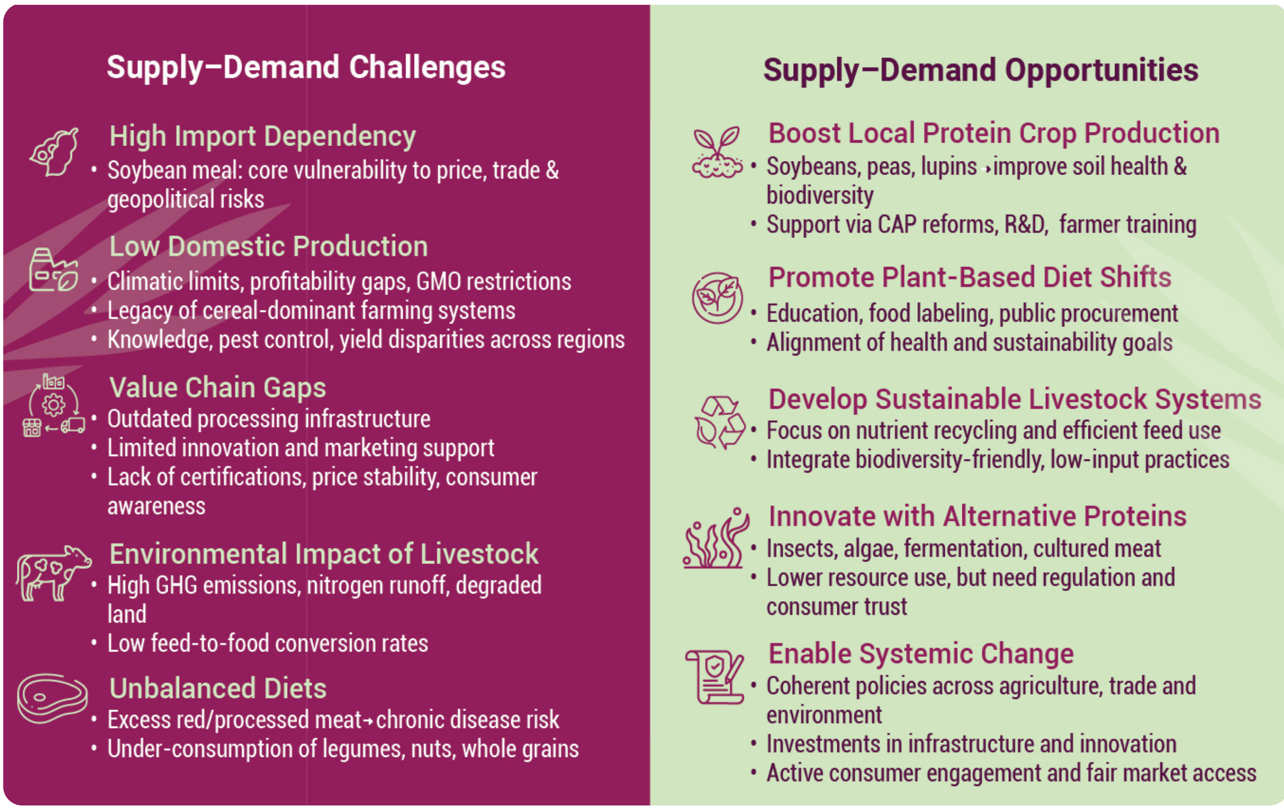

Figure 2. Protein Supply-Demand Challenges & Opportunities in the EU

How to reduce the protein deficit?

To reduce its protein deficit, the EU protein strategy is considering three main actions:

1. **Working to boost domestic production** by increasing financial support for farmers through the CAP: This has led to expanded cultivation of protein crops like soybeans and pulses, which are expected to reduce reliance on imports, although full independence, especially for oilseeds, remains unlikely [14,19].
2. **Developing alternative protein sources**: These include microbial proteins derived from bacteria and fungi, which are environmentally efficient but currently energy-intensive to produce [28,29]. Insects are gaining ground as a protein source for animal feed and algae are being promoted for their nutritional value and sustainability, particularly in aquaculture [26,27].
3. **Improving sustainability in food and feed systems**: This includes encouraging more plant-based diets, reducing meat consumption and promoting the use of food waste and by-products in animal feed (a practice known as circular feed)[18,23]. Technological innovations, such as digital tools and feed additives, are also being used to optimise protein use and lower GHG emissions [7,8,15,21].

The way protein is both produced and consumed in the EU requires consideration. A food systems approach, combining supply-side and demand-side actions, is crucial to transitioning towards a sustainable and resilient EU protein supply [2,4]. This transition should be undertaken from a **multifactorial integrated perspective**, considering the medium- and long-term impacts. This requires keeping a challenging balance between the interests of producers, consumers, the environment and the EU's sovereignty.

This is not only related with research but will require a comprehensive plan integrating also policy and on the ground efforts to create a more self-sufficient and sustainable EU protein system, while at the same time diversifying imports[4].

How can we mainstream alternative proteins in Europe?

A recently published analysis by a Horizon Europe funded project appoints the following **strategic pathways to mainstream alternative** proteins in Europe within the next two decades [26]:

- Leveraging National Commitments: Aligning alternative protein initiatives with national policies and sustainability goals;
- Ensuring Price Parity and Beyond: Making alternative proteins economically competitive with conventional proteins;
- Nudging Behavioural Change: Utilizing behavioural insights to encourage consumer adoption of alternative proteins;
- Accelerating Alternative Proteins Development: Investing in R&I to enhance the quality, variety, and appeal of alternative proteins;
- Empowering Food and Health Professionals: Engaging key influencers to advocate for and educate about alternative proteins.

CONSUMERS' ROLE AND POTENTIAL AS DRIVERS TOWARDS EU PROTEIN TRANSITION

Consumers are at the heart of Europe's shift toward more sustainable and diversified sources of protein. As the EU aims to reduce its reliance on imported proteins and address environmental and health challenges, **changing consumption patterns is just as crucial as transforming agricultural production** [2,8].

Alternative proteins (including plant-based, microbial, insect-based, marine and cultured options) hold promise for reducing GHG emissions, land use and water consumption [27,28]. However, consumer uptake remains limited. A recent systematic review highlights that factors such as taste, price, familiarity, health perceptions and social norms all strongly influence whether people accept and choose these new protein sources[18].

While awareness of the need for change is growing, many consumers are still hesitant. Research shows that concerns about the "naturalness" of products, scepticism about new food technologies and lack of clear labelling can create resistance [17,30]. This means that simply offering alternative proteins is not enough, there must also be a shift in values, preferences and habits.

Several **socio-economic factors** have also contributed to shape current consumption patterns, including established cultural preferences, rising disposable income enabling greater access to meat products, convenience factors influenced by marketing strategies, established supply chain structures and the relative consumer prices of animal and plant-based protein sources[15].

European bodies have recognised this challenge, highlighting the importance of improving food literacy, making sustainable choices easier and ensuring that new products align with people's tastes and values [9,26]. Initiatives such as public education, school meals featuring plant proteins and clearer product information are already helping.

At the same time, **consumers can influence change** by supporting local protein sources, exploring more plant-based meals and demanding transparency and sustainability from food producers. When consumers act together, they can shape markets and accelerate the transition. The *protein transition* is a shared effort. Producers, researchers, policymakers and consumers each have a role to play.

ALTERNATIVE PROTEIN SOURCES POTENTIAL

Global demand for food is expected to nearly double by 2050. **Alternative proteins could be a sustainable solution** to provide food security with restricted production resources [7]. However, the growth and consumer intake of alternative proteins remains limited.

Alternative protein sources, ranging from non-traditional plant-based proteins to microbial, insect, cultured meat, algae and by-products, hold significant **potential to support the EU's shift toward a more sustainable, resilient and autonomous protein system** [26,29]. These emerging proteins can play a critical role in addressing environmental challenges (such as GHG emissions, land use and biodiversity loss), reducing import dependency and meeting consumer demand for healthier, lower-impact food options.

By 2035, alternative proteins may capture 11-22% of the global protein market, with Europe being a leading region. Algae have strong potential to meet protein demand and partially replace soy in feed. Insect-based protein is expected to reach 3.1 million tonnes by 2030, mainly as feed, replacing portions of fishmeal and conventional proteins. Microbial fermentation could produce 22 million tonnes globally by 2035, contributing 2.5% to the protein market. Cultured meat faces slow growth, with limited production projected before 2051; most estimates suggest it will remain a niche contributor through mid-century [27,28].

Overall, **protein supply is expected to grow globally**, but Europe's shift toward plant and alternative proteins reflects both environmental pressures and changing dietary trends. However, when supported by integrated policies and R&I ecosystems, they can contribute to a climate-smart, competitive and socially acceptable protein future for EU [4,26].

1.2. Policy Context

Globally, sustainable protein production and consumption are considered critical levers for achieving the **Sustainable Development Goals (SDGs)** and the **Paris Agreement**. The **UN report "The Future is Now"** (United Nations, 2019) identifies "sustainable food systems and healthy nutrition" as one of six key entry points for transformation. In recent years, the food system's protein sector has gained increasing political momentum at multiple levels of governance. In the EU, protein supply and demand is becoming a **strategic** issue across multiple policy domains, including agriculture, trade, health & nutrition, environment and Research & Innovation (R&I) (e.g. EC, JRC, 2024). Efforts aim to reduce import dependencies for food and feed and to promote dietary shifts towards diversified and sustainable protein sources produced in the EU [1,15].

For the last decades, the Common Agricultural Policy (CAP) and the Common Fisheries Policy (CFP) have been the main sectoral policies shaping EU food production. In the field of health and nutrition policy, the EU Cancer Plan serves as a central strategic document. However, jurisdiction over nutrition policy primarily lies with the Member States. National-level action is typically implemented through nutrition programmes, with food-based dietary guidelines functioning as a key policy tool. These guidelines also include recommendations on the quantity and composition of protein consumption.

The publication of the *European Green Deal* and the *Farm to Fork Strategy* (F2F) in 2019 marked a shift towards a more systemic policy approach that integrates agricultural and nutritional objectives within a single framework. In the context of protein, this includes promoting sustainable farming practices, alternative protein sources and more sustainable consumer choices. This approach was also reflected in the following programming period of the CAP, which serves as a supportive policy framework encouraging Member States to implement measures that promote the cultivation of protein crops in the EU, for example, through coupled income support, sectoral interventions, the design of eco-schemes, or investment subsidies. A legal framework for a sustainable food system (FSFS), announced as part of the *Farm to Fork Strategy* to create a legally binding, EU-wide structure and to strengthen the directionality and coherence of EU agri-food policy, has yet to be published.

The recently published **Vision for Agriculture and Food** by the European Commission (February 2025) emphasises the critical role of the protein subsystem and keeps an integrated approach that links the entire value chain. In light of the current geopolitical situation, the vision particularly stresses the need to expand and diversify protein production across the EU in alignment with sustainability goals, in order to strengthen food sovereignty.

The European Commission also announced the development of a comprehensive plan to establish a self-sufficient and sustainable EU protein system, addressing both environmental and strategic resilience challenges. This initiative will take a holistic approach, addressing the entire protein value chain within the agri-food system. The focus will be on boosting domestic production to strengthen self-sufficiency while diversifying imports to reduce reliance on external sources and enhance food security. Drawing from research and real-world practices, it will outline a path to enhance the sector's competitiveness, sustainability and profitability. While some EU Member States have already developed national protein strategies, the establishment of an EU-wide, food systems-oriented strategy would represent a significant milestone towards greater coordination across the EU.

The strategic approaches and announcements mentioned above provide important guidance for a more holistic policy framework for protein value chains within the food system. However, the coherent coordination of policies, their specific objectives and measures across relevant sectors remains a key challenge. Sector-specific objectives can lead to tensions or inefficiencies if they are not sufficiently coordinated. In this context, for example, the Renewable Energy Directive - in particular measures to promote biofuels - highlights the importance of careful coordination between energy, agricultural and food policies in order to manage land use interactions. A well-designed policy mix approach that takes into account cross-sectoral synergies and trade-offs will be crucial to improving policy coherence and supporting the long-term resilience of the EU's food and protein system.

Figure 3. below, developed by the SCAR Protein TF, gives an overview of relvant policy documents that provide guidance and shape the protein system on member state and EU level:

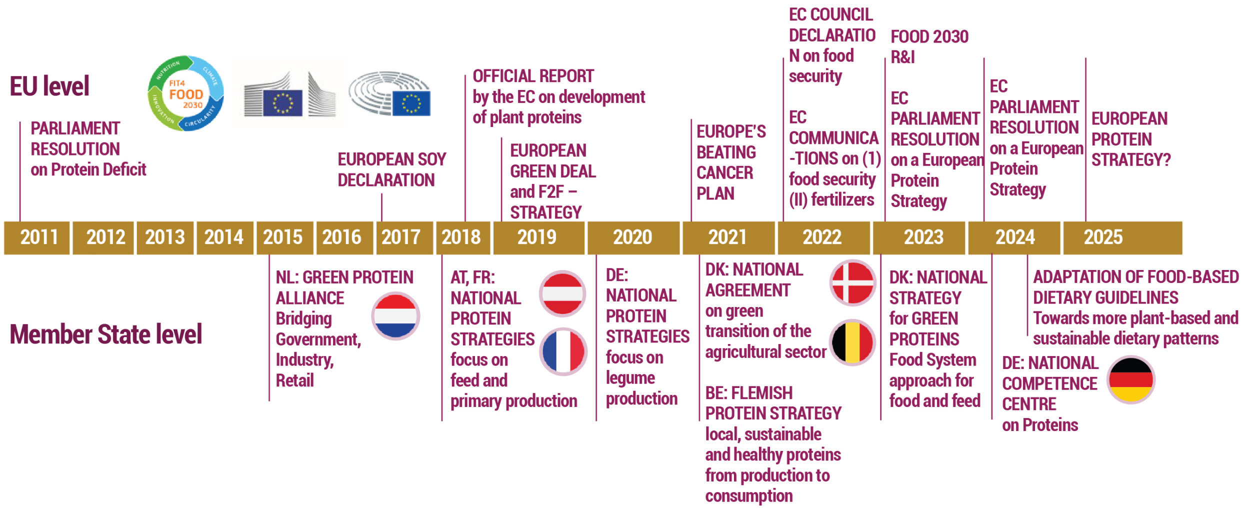

Figure 3. Overview of relevant policy references shaping the EU protein system on member state and EU level

Key ongoing challenges in protein related EU-Agri Food policies are:

I. Integrating the **entire value chain** into the development of **holistic strategies** and the corresponding mainstreaming into **action plans** and **policy measures**,
I. Cross-sectoral alignment of policies within a coherent policy framework by using a **food system** and **policy mix approach**,
II. Addressing innovation, scaling up, exnovation of existing structures and measures that no longer meet objectives, as well as managing potential trade-offs within a consistent policy mix.

2. SCOPE & OBJECTIVE

2.1. Research & Innovation (R&I) towards Protein Transition in the EU

Europe's *protein transition* depends on **robust and well-aligned R&I strategies** which enables the development of viable alternatives, empowers local production and supports societal uptake. By bridging the gap between innovation, policy and consumption, R&I helps build a climate-resilient, nutritionally balanced and economically viable protein future for Europe [21,24].

ROLE OF R&I IN SUPPORTING SUSTAINABLE PROTEIN PRODUCTION

R&I play a central role in fostering protein transition, tackling environmental, economic and social challenges while unlocking opportunities for sustainability and resilience. The identification and development of alternative protein sources, such as legumes, pseudo-cereals, insects and microbial proteins, require scientific progress and targeted innovation efforts. Each source presents distinct opportunities and challenges that necessitate interdisciplinary research, from agronomy and breeding to food technology and nutrition science to meet both food and feed demands. However, technical advances alone are not sufficient[31]. **The adoption of alternative protein sources is often hindered by systemic constraints,** including economic, organisational and institutional lock-ins. These challenges underscore the importance of R&I not only in developing new solutions but also in addressing the socio-technical conditions that shape innovation uptake, consumer acceptance and value chain transformation. Within this context, the Food 2030 EU policy framework identifies "Alternative proteins for dietary shift" as one of its eleven key pathways to support the transition to sustainable, healthy and resilient food systems. This reinforces the strategic relevance of R&I in promoting protein diversification as a means to achieve EU goals on climate, health and food security.

R&I IN ALTERNATIVE PROTEINS

Given the limited availability of land in the EU, R&I in alternative protein sources is essential to support food security and sustainability. Advances in technology have enabled the development of food products that closely replicate the taste and nutritional value of traditional animal-based foods, while technology can play a crucial role in reducing the EU's external dependencies and strengthening the resilience of agri-food systems [24].

Despite progress, **several knowledge gaps remain**: Algae species are still under-researched and reliable data on the EU algae sector is limited; Microorganism-based proteins produced via precision fermentation face challenges in industrial scalability; Cultured meat requires further risk assessments and a clearer understanding of its sustainability and health impacts; Plant-based proteins continue to face barriers related to taste, texture and cost, while the insect protein sector needs more evidence on farming methods, economic viability, food safety, nutrition and consumer acceptance. R&I efforts should focus on improving product quality, reducing production costs, increasing market uptake and integrating consumer perspectives into innovation processes [24].

Addressing Challenges and Unlocking Opportunities

A fundamental transformation of the ways we produce and consume food in Europe is needed [32]. Recent studies emphasise that **shifting to a diverse mix of plant-based, microbial, cultivated and insect-derived proteins** requires not only novel technologies but also interdisciplinary R&I efforts spanning food systems, behavioural science, agronomy and processing [3,29].

R&I can help **overcome key barriers**:

- Improving protein crop yields and agronomic viability, especially for legumes, oilseeds and cereals.
- Enhancing product taste, texture and nutrition to drive consumer acceptance.
- Scaling up circular and climate-smart production systems, including side-stream valorisation and microbial fermentation.
- Understanding consumption patterns and promoting dietary shifts via nudging, education and food environments.

DRIVING SELF-SUFFICIENCY AND SUSTAINABILITY

To move toward a self-sufficient and sustainable EU protein system, **R&I must address supply chain gaps and promote integrated approaches from farm to fork**. The EC approach for reducing plant protein dependency outlines EU-funded initiatives that support: Breeding and adapting protein crops to European conditions; Innovations in feed formulation to reduce reliance on imported soy; and Development of new food products that meet nutritional, sensory and safety standards [14,24].

According to recent evaluations on feeding strategies and protein balance, **increasing on-farm and regional production** of protein crops like peas, faba beans and lupins, alongside investments in processing infrastructure, is critical. Equally, innovations in protein processing, storage and market access will enhance the competitiveness of EU-grown proteins [12,21].

The CAP Strategic Plans and national initiatives increasingly prioritise **support for protein diversification**, but coordinated R&I is needed to ensure coherence across food, feed and bioeconomy sectors [4,19].

2.2. Coexistence and Diversification approach towards EU Protein Transition

The SCAR Protein Task Force (TF) appeals to a **coexistence and diversification approach** which implies an **integrated and holistic** food systems perspective to protein sources. This involves facing transition scenarios that consider all protein sources for food and feed, emphasising socio-economic, nutritional, environmental and health impacts. Strategically, it aims to enhance European food and feed sovereignty by promoting alternative and regionally produced proteins.

Rather than promoting a full substitution of conventional proteins, this approach encourages **complementarity**, recognising that different regions, cultures and ecosystems require tailored protein strategies. Diversification strengthens resilience, reduces dependency on imported feed proteins and supports local production systems.

The SCAR Protein TF advocates for a **systems-based perspective** that connects food and feed, avoids isolated policy-making and manages trade-offs between environmental, economic and social objectives. This means simultaneously supporting innovation in novel protein sources while improving the sustainability of traditional livestock systems.

Consumers also play a role in enabling coexistence. By providing access to a wider range of nutritional, affordable and clearly labelled protein options, the promotion of healthy and sustainable food environments, can support gradual dietary shifts without forcing uniform change. This inclusive approach increases social acceptability and reduces resistance to dietary change. Associated with this, the potential effect of parallel diversification of the waste that can be produced would also have to be anticipated and considered in terms of sustainability.

In summary, a coexistence and diversification approach will allow the EU to pursue a **flexible, resilient and inclusive protein transition**, one that **balances R&I with tradition and aligns with the EU's broader sustainability and food security goals**.

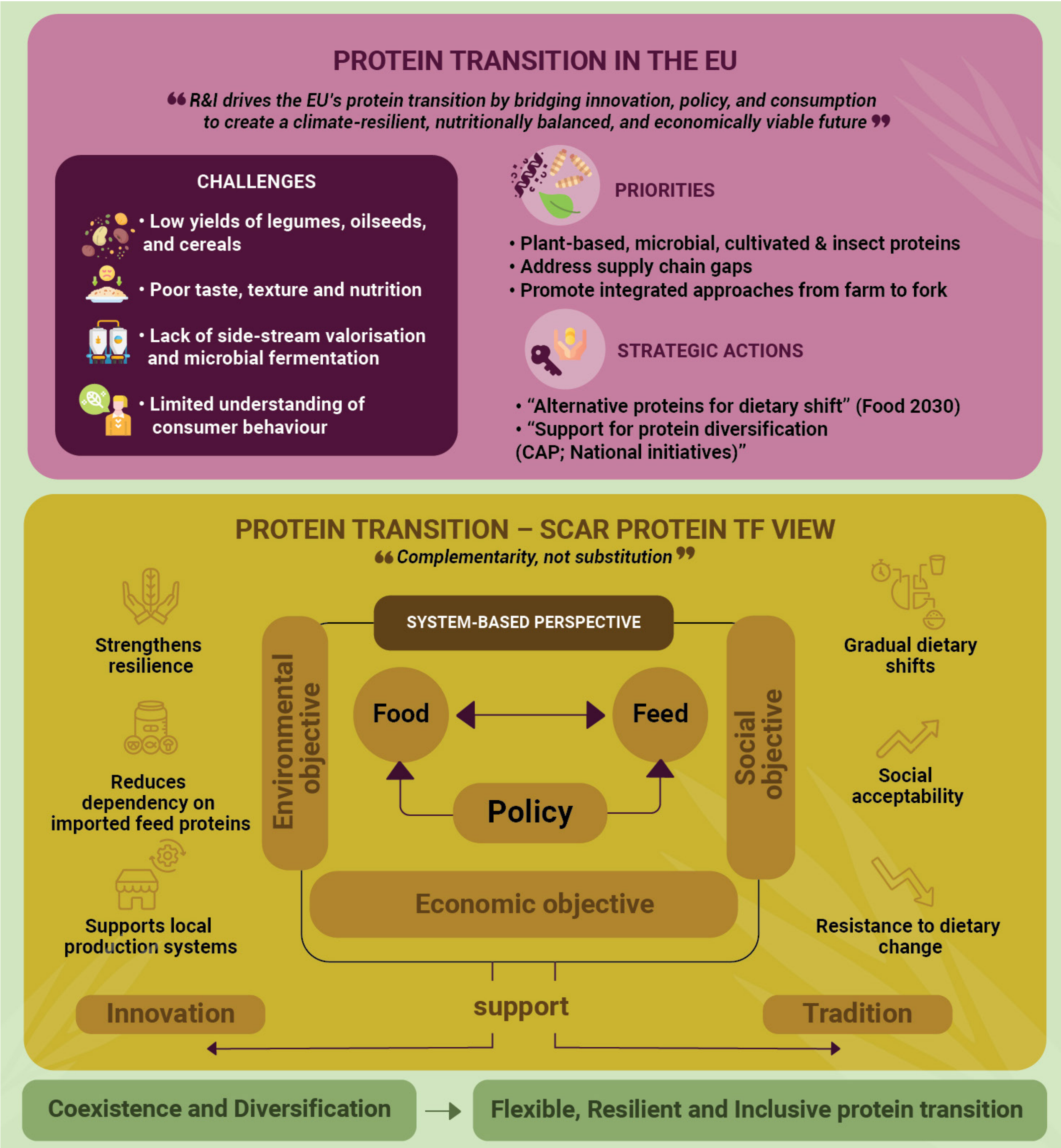

Figure 4. R&I towards Protein Transition in the EU, the SCAR Protein TF view

2.3. Objective & Methodology

The overarching objective of the present document is to **examine how European R&I can foster the diversification, sustainability and strategic autonomy through the protein value chain within the EU**. It seeks to provide a **comprehensive and forward-looking understanding of the current landscape** of protein sources, both plant-based and non-plant-based and to **identify key pathways for enhancing resilience and sustainability** across the European food system.

Specifically, this Policy Review and Analysis aims to:

- Review the current landscape of protein production and consumption in Europe, assessing trends, drivers and challenges shaping the EU protein system
- Conduct a state-of-the-art analysis of R&I activities related to alternative protein sources, encompassing both plant-based (e.g., emerging or underutilised crops, pseudo-cereals, oilseeds and pulses) and non-plant-based sources (e.g., microbial, algal and insect proteins).
- Integrate relevant insights from a Portfolio Analysis specifically conducted in parallel for the SCAR Protein TF and supported by the *RefreSCAR* project.
- Deconstruct and analyse the protein value chain into its key different segments for primary production, feed and food to identify specific challenges, bottlenecks and innovation opportunities within each.
- Sketch tentative potential actions and strategic directions to address identified gaps and leverage emerging opportunities.
- Provide a set of targeted policy recommendations for strengthening R&I on protein transition in alignment with the goals of strategic autonomy and sustainability in EU protein production and consistent with the rational and expertise of the SCAR Protein TF.

The methodology combines two complementary components:

1. **State-of-the-art review**: TF members have developed thematic syntheses based on expert knowledge in their respective domains supported by peer-reviewed scientific literature. This covers the full spectrum of alternative protein sources, integrating aspects of production, processing, nutrition, sustainability, market uptake and consumer acceptance. The analysis highlights key scientific advances, persistent challenges and innovation barriers along the protein value chain.
2. **In-house analysis and reflection**: Drawing on the collective expertise of the TF members, the group has identified major challenges, opportunities and preliminary recommendations for advancing R&I on alternative proteins in Europe. This qualitative assessment builds upon the group's shared understanding of the current R&I landscape, complemented by selected insights from the Portfolio Analysis of EU-funded projects. While these portfolio findings have informed the reflection, a more detailed and systematic analysis is provided in a dedicated report developed in collaboration with RefreSCAR.

Together, these complementary approaches provide a robust basis for **drawing actionable insights and developing strategic recommendations** to guide future R&I agendas and policy directions towards a more autonomous, sustainable and resilient European protein system.

3. STATE OF THE ART ON R&I FOR ALTERNATIVE PROTEIN SOURCES

3.1. Alternative crop protein sources in Europe

In the context of climate change, resource scarcity and evolving dietary demands, **alternative crops**, including pulses (such as peas, faba beans, lentils, chickpeas), cereals like sorghum and millet, pseudocereals (e.g. quinoa, amaranth) and oilseeds (such as hempseed, flaxseed, chia, sunflower, pumpkin, rapeseed/canola, safflower and camelina), are gaining increasing attention. These crops offer potential solutions for sustainable agriculture, improved nutrition, and/or diversification of the food system. However, each presents a diverse range of agronomic, nutritional, processing, safety, consumer and sustainability attributes, each accompanied by specific challenges and opportunities.

AGRONOMIC PRODUCTION

Sorghum stands out for its resilience to drought and poor soils, making it an attractive substitute for maize (as feed livestock) in the context of climate change. Model predictions suggest that yields in northern Europe could increase by up to 3 tonnes per hectare by 2100, enhancing **feed security** across the continent [33]. Nonetheless, the crop remains susceptible to abiotic stresses like heat and biotic threats such as fungal contamination, especially from *Aspergillus* and *Fusarium* species [34]. Moreover, the availability of improved seed varieties and the dissemination of postharvest technology remain limited, particularly in smallholder enterprises [35].

Pseudocereals, including quinoa and amaranth, are similarly adaptable to diverse climatic conditions and require fewer inputs (e.g. water) than conventional cereals. However, their cultivation is hampered by specific constraints such as disease susceptibility (less the case for quinoa) and the need for specialised post-harvest handling due to unique small seed morphologies [36].

Oilseeds, including flax and camelina, are well-suited for marginal lands and low-input systems. Camelina, for example, can be cultivated with minimal inputs and presents an opportunity to diversify protein supply in the EU [37]. Nevertheless, many oilseed crops, including flax and rapeseed, struggle with low genetic diversity, variable yields and the persistent presence of anti-nutritional compounds which could be resolved by advancements in breeding and/or processing (see further) [38,39].

Pulses, such as peas, faba beans, lentils and chickpeas, are widely recognised for their multiple agronomic and environmental benefits, including nitrogen fixation, soil health improvement and their role in low-input cropping systems. Despite these advantages, pulses have historically received limited investment and development in Western countries. Compared to soybeans, whose global production has surged from 70 million tonnes in the 1960s to nearly 400 million today, most other pulse species have seen only marginal increases in cultivation. This disparity has been described as a form of **technological lock-in**, wherein institutional, economic and market dynamics reinforce the dominance of certain crops like soybean at the expense of others[31]. Such lock-in has limited varietal improvement, agronomic innovation and infrastructure dedicated to pulse crops in Europe. In recent years, renewed interest, driven by the need for plant-based protein sources and agroecological transition, has led to a modest resurgence in pulse production in several EU countries, although challenges persist in scaling up their cultivation. These include climate sensitivity, disease pressures and limited access to improved cultivars suited to local agro-climatic conditions

NUTRITIONAL VALUE

Sorghum is a gluten-free cereal rich in phenolics and antioxidants. It holds promise as a functional food component for managing metabolic conditions like diabetes [40]. However, its nutritional composition varies considerably due to differences in soil, genotype and agronomic management. Frequently low amounts of lysine are identified but (fairly) high concentrations in cysteine and methionine, two other essential amino acids. The presence of phenolic compounds may impair nutrient **bioavailability** and cooking the grains during processing may reduce the digestibility of the **sorghum** proteins [40,41].

Pseudocereals like quinoa and amaranth offer high-quality proteins with a favorable amino acid profile and large quantities of sulfur-rich essential amino acids. Regarding digestibility, pseudocereal proteins are superior to cereal proteins and equivalent to casein. They serve as excellent ingredients in gluten-free diets and have strong potential for improving food system **nutrition** [42].

Oilseeds, particularly pumpkin seeds, which contain up to 56% protein and sunflower seeds with about 37% protein, are significant sources of plant-based nutrition. Oil seed protein isolates offer rich contents in arginine, valine, tryptophan, glutamic acid, cysteine, serine and proline. The presence of significant amounts of polyphenols, may impair protein digestibility, however extraction of proteins from oilseed cakes can be beneficial in this regard [43]. Hemp and flax show significant amounts of antinutrient glucosinolates of which the concentrations can be influenced by heat or fermentation processing (see also section Safety). Their proteins have demonstrated cardiovascular and anti-inflammatory properties, making them attractive for both general and clinical **nutrition** [39,44].

Pulses are a rich source of plant protein, with average protein contents ranging from 20% to 30% depending on the species and variety. They contain significant amounts of lysine, an essential amino acid often limited in cereal grains, making them complementary to cereal-based diets. Additionally, pulses offer complex carbohydrates, dietary fiber and important micronutrients, including iron, zinc and B vitamins. However, their nutritional value can be constrained by the presence of anti-nutritional factors such as phytic acid, tannins and trypsin inhibitors, which reduce mineral bioavailability and protein digestibility. Traditional and modern processing techniques such as soaking, fermentation and thermal treatment can mitigate these effects [45,46].

PROCESSING AND FOOD APPLICATIONS

The **processing** of sorghum into food products is limited by poor milling efficiency, short shelf life and challenges in preserving sensory quality. Processing technologies such as roasting and fermentation have shown promise in improving the bioactivity and functional characteristics of sorghum-based ingredients by, amongst others, reducing bioactive compound concentrations [47]. However, technical barriers such as seed polishing and low palatability compared to wheat flour and rice continue to hinder its industrial uptake as raw material for food production [35].

For **pseudocereals**, their small and structurally complex seeds require tailored milling strategies. Amaranth's dense hull demands moisture adjustments before processing, while quinoa's bitter-tasting saponins necessitate extensive water-intensive washing and drying. These factors raise both processing complexity and cost. Additionally, pseudocereal proteins do not possess any network forming properties making it for example difficult to create volume in bakery products [36].

Biorefinery of oilseed protein is another challenging area. Conventional solvent extraction methods, such as hexane use and other applied processing conditions (temperature, shear, ionic strength, pH, etc.) compromise protein integrity and raise environmental concerns. Moreover, proteins are often degraded altering their confirmation and functional properties (emulsifying, gelling, foaming, texturising and fat-binding properties). Novel methods such as enzyme-assisted and supercritical CO_2 extraction are being developed to improve yield and maintain functional properties [48,49].

The industrial **valorisation of pulses** is often constrained by challenges in processing, especially in protein extraction and functionalisation. Traditionally, wet fractionation has been the dominant method used to obtain high-purity protein isolates from pulses. This technique generally involves solubilising proteins in water followed by precipitation and drying, requiring substantial amounts of water and energy. While it yields products with high protein concentrations, the process is resource-intensive and raises sustainability concerns. Dry fractionation has emerged as a promising alternative that aligns more closely with sustainable processing goals. It typically involves milling and air classification to separate protein-rich and starch-rich fractions without the use of solvents. Though it results in protein concentrates with lower purity compared to isolates, it has the advantage of better preserving native protein functionality (e.g., solubility, emulsifying capacity), which is often degraded in wet processes[50].

In general, frequently knowledge is lacking about the impact of biorefinery processes of alternative crops on their protein quality and functionality.

SAFETY

Food safety remains a concern for sorghum due to frequent contamination with aflatoxins and fumonisins. Despite this, many countries lack regulatory thresholds for mycotoxins in sorghum, posing risks to public health [34]. Moreover, in general food producers lack the tools, data and standardised methods to manage mycotoxin risks in (processed) alternative crop-based food products (e.g. plant-based meat alternatives) and no clear (regulatory) benchmarks for safe food formulation are yet in place. Also, there is only limited knowledge on how processing influences mycotoxin levels.

Oilseeds such as rapeseed and flax contain **anti-nutritional factors** like trypsin inhibitors, oligosaccharides, phytates and tannins all of which necessitate careful processing to ensure safety [51]. Processing interventions have been developed to remove or reduce these anti-nutritional factors, but efficiency, costs, sustainability and scalability of some of these processing techniques remain hurdles [39].

On the other hand, some oilseeds like hemp, as well as rapeseed, contain **allergenic factors**, directly affecting the acceptability of the oilseeds and their protein rich by-products for human consumption. Processing techniques, such as heat treatment, are often employed to mitigate, but knowledge on impact of processing techniques on allergic components is limited, especially for oilseed and other alternative protein rich crops[39].

Plant-based ingredients are also microbiologically contaminated via soil or vegetation where *B. cereus* spores are naturally present [52]. There also seems to be an association between *L. monocytogenes* and sunflower seeds. In 2016, there were 196 recalls in the USA related to *L. monocytogenes* contamination of foods of which 50 were due to contaminated sunflower seeds and derived products including granola bars and sunflower butter [53]. There are knowledge gaps for other (alternative) plant protein sources. Additionally, knowledge about the impact of processing on the **microbial load** of plant-based alternatives is limited, especially regarding survival of thermoresistant germs or spores.

CONSUMER ACCEPTANCE

Consumer **familiarity and perception** play a critical role in the market integration of alternative crops. Millet, for instance, is often viewed as a subsistence or "poor man's" food, limiting its appeal in human diets. Preparation complexity, limited availability and dislike of taste of sorghum and millet also contribute to limited adoption [54]. Issues of bitter taste and sensory attributes (e.g. dark color) challenge the wider use of oilseed-derived proteins, especially flax and rapeseed, which may require further refinement for broad consumer acceptance [55].

Conversely, increasing demand for healthy and nutritious plant-based diets has opened up new opportunities for pseudocereals (e.g. quinoa) and oilseeds (e.g. flaxseed cake). Their application **in functional foods**, such as meat substitutes, bakery products and dairy alternatives, has grown, with several examples demonstrating their successful integration into these formats [36,44].

SUSTAINABILITY

From an environmental standpoint, these alternative crops align well with the goals of **sustainable agriculture**. Sorghum, millet, pseudocereals and oilseeds can be cultivated in low-input systems and on marginal lands, thereby minimising their ecological footprint [33,36,37,42]. Sorghum in particular offers lower water and carbon requirements compared to maize and its application in biodegradable packaging materials replacing synthetic polymers represents an innovative and sustainable use beyond food [40].

Oilseed cakes as residual byproducts from oil extraction are currently underutilised in human food systems. Yet they present an important opportunity to reduce waste, enhance protein availability and provide economic value to processors and farmers. Their valorisation into protein-rich food ingredients could mitigate reliance on animal proteins and contribute to climate change mitigation [43,51].

Alternative crops such as sorghum, millet, pseudocereals, pulses and various oilseeds and each of their protein rich fractions offer substantial potential to diversify food systems, improve human nutrition and contribute to environmental sustainability. However, realising this potential will require targeted innovations in crop breeding, processing technologies, safety assurance and consumer education. Investment in fundamental and applied research and supportive policy frameworks is essential to overcome the above identified challenges and to fully integrate these crops into modern food systems.

3.2. Alternative non-crop protein sources in Europe

PRODUCTION

Alternative non-crop protein sources, including **algae** (both seaweeds and microalgae), **insects**, **microbial fermentation products** (e.g. **mycoprotein**) and **cultured meat**, currently represent only a small fraction of Europe's protein output, but production is growing. Europe's algae sector remains modest in global terms, accounting for roughly 1% of global algae biomass supply. In 2015, European seaweed production was estimated at around 230.000 tonnes (wet weight), while the combined algae sector (microalgae and seaweeds) had an estimated market value of EUR 6,3 billion, with food products representing the largest segment. The market for seaweed-based foods has been expanding steadily with annual growth rates of 7–10%. **Insect** farming is expanding, primarily for animal feed: EU output of insects for feed roughly doubled from about 5.000 tonnes in 2019 to approximately 9.500 tonnes in 2022. Several **insect** species (e.g. mealworm, cricket, locust) have been authorised as novel foods, laying the groundwork for a nascent edible insect industry in the EU. For instance, a fungal mycoprotein (sold as Quorn™) has been produced at scale for decades, with a single facility in the EU producing around 22,000 tonnes per year. This sector has achieved a high technology readiness level (TRL 9), indicating proven commercial-scale production and multiple market applications in Europe. In parallel, Europe is also seeing growing activity in precision-fermentation platforms that produce specific food proteins and ingredients, such as enzymes, dairy proteins (e.g. caseins and whey proteins), egg proteins (e.g. ovalbumin) and heme-type proteins like myoglobin. Global investments in fermentation for alternative proteins between 2013 and 2022 amounted to around USD 2.9 billion in North America and USD 0.4 billion in Europe, while the number of biomass and precision-fermentation companies increased from only seven before 2013 to 132 in 2022, with just under half of these companies based in Europe[29]. More recent industry data from The Good Food Institute indicate that, by the end of 2024, around 165 fermentation companies were focused predominantly on alternative proteins worldwide, having attracted approximately USD 4.8 billion in cumulative investment and about USD 650 million in private funding in 2024 alone (GFI, 2025), further underscoring the rapid expansion and consolidation of this sector. This illustrates both the rapid expansion of the sector and Europe's growing role in hosting fermentation-based alternative protein companies and infrastructure. By contrast, **cultured meat** remains in the R&D or pilot stage: no cultured meat products have yet been approved for sale in Europe and only small pilot quantities are being produced while companies seek regulatory clearance and scale-up solutions [29].

Recognising the need to accelerate alternative proteins, the EU and Member States are investing in research and infrastructure. Since 2015, about 644 million € has been directed to 125 projects on sustainable proteins (including novel sources) under Horizon 2020 and Horizon Europe programmes. Many EU countries have also launched national strategies and initiatives to support alternative proteins alongside plant proteins, aiming to build a more resilient and self-reliant protein supply system [56].

NUTRITIONAL VALUE

Alternative protein sources offer favourable nutritional profiles, although with some variations compared to conventional proteins. Insects and microalgae typically have high protein content and contain all essential amino acids, but **their overall protein quality (considering both amino acid profile and digestibility) is often somewhat lower than that of milk or meat proteins**, partly due to factors such as chitin or cell wall components. These sources also provide dietary fibre and beneficial micronutrients. For example, edible **insects** and **algae** contain vitamins (B12, A, etc.) and minerals (iron, zinc, calcium) in proportions that can meet or exceed those found in meat [29].

Mycoprotein (fermentative fungal protein) offers high-quality protein with an amino acid profile comparable to animal protein, along with a notable fibre content and low fat. Its protein is slightly less digestible than casein, but regular consumption has shown health benefits such as improved blood cholesterol and glycaemic response. **Cultured meat** is expected to have a nutritional composition essentially identical to conventional meat muscle, since it is biologically the same tissue grown under controlled conditions [29].

Overall, non-crop alternatives can substantially contribute to human protein intake and deliver important micronutrients. However, ongoing research is examining how processing may affect their nutrient bioavailability and how to optimise feed and fermentation media to enhance nutritional quality [29].

PROCESSING

The production and processing methods for many non-crop proteins are advancing, but scaling up remains a key challenge. **Insects**, **algae** and **mycoproteins** already utilise relatively well-established cultivation and processing techniques and have reached advanced technology readiness with multiple commercial applications in food or feed [29].

For example, large **insect-rearing** facilities use automated systems to breed and harvest larvae, which are then dried or defatted into protein meal for feed. **Algae** cultivation employs open ponds or photobioreactors and in the EU algae-derived foods (such as seaweed snacks or spirulina powder) have achieved higher market maturity than algae-based animal feed additives, for which processing capacity is still developing. Conversely, **insects** are currently produced at greater scale for feed use (e.g. in aquaculture or poultry diets) than for direct human food, reflecting the easier market entry on the feed side[29].

Mycoprotein fermentation relies on established bioprocessing, using large industrial fermenters where fungi convert agricultural substrates into biomass, followed by downstream processing (heat treatment, drying, texturising) into food products. Europe already hosts some of the world's largest alternative protein fermenters dedicated to **mycoprotein** production[29].

In contrast, **cultured meat** requires cutting-edge biotechnologies, including stem cell culture, growth factor inputs and bioreactors, that are not yet optimised for mass food production. There is currently a lack of food-grade bioreactor capacity and cost-efficient cell culture media at the scale needed for industrial cultured meat manufacturing. Across all these novel protein sectors, scaling up production while controlling costs is a common hurdle. Processing constraints, for instance harvesting and drying **microalgae** or maintaining sterile conditions in cell culture, call for further innovation. Investments in dedicated infrastructure (e.g. large-scale fermentation facilities and **insect breeding** hubs) and process improvements are needed to achieve economies of scale[29].

Policymakers have noted that expanding processing capacity and reducing production bottlenecks will be crucial for alternative proteins to compete with well-established protein sources [21,29].

FOOD SAFETY

Ensuring food and feed safety is crucial for building trust in non-traditional protein sources. In the EU, novel foods regulation requires a thorough safety assessment for new protein sources before they reach the consumer market. Edible **insects**, for example, must be authorised as novel foods. To date, four **insect** species (such as the yellow mealworm and house cricket) have received EU approval for human consumption after evaluation of their safety. Producers must adhere to strict hygiene and processing standards equivalent to those for traditional livestock products and may only use approved feed substrates for rearing insects to avoid contamination with pathogens or heavy metals [29].

A primary safety consideration is allergenicity. **Insects** contain substances such as tropomyosin and chitin that can trigger allergic reactions, especially in individuals allergic to crustacean shellfish, so clear labelling and further research on allergen management are needed. **Algae** and single-cell microbes intended for food also undergo safety assessments. Certain **microalgae** can produce toxins or accumulate contaminants if grown in uncontrolled environments, so producers must carefully control growing conditions and post-harvest processing to ensure purity, for example by testing for marine biotoxins or heavy metals in seaweed. Many **algae** and microbial products have low inherent allergenicity and some (such as the spirulina cyanobacteria) have long histories of safe use, but novel strains or fermentation products are evaluated case by case under EU novel food rules [29].

Non-crop protein products that are already established in the market have generally demonstrated a good safety record. For instance, **mycoprotein-based** foods have been sold in Europe for over 20 years with no significant food safety incidents reported. This is attributed to rigorous production controls, including fermentation under sterile conditions followed by heat treatment and toxicity testing conducted during the novel food approval process. **Cultured meat**, on the other hand, is still awaiting regulatory approval in Europe and will be subject to very strict safety scrutiny. Regulators will examine aspects such as the source and integrity of the cell lines, the composition of culture media and the absence of microbiological contamination in the final product.

At the same time, stakeholders from the microbial protein sector point out that, despite these well-established safety frameworks, they face regulatory and procedural hurdles that may slow down market entry. They therefore call for a more stimulating and predictable regulatory environment, including adequate funding and faster, science-based authorisation procedures, so that microbial proteins can fully contribute to more sustainable agriculture, the development of a green bioeconomy and climate change mitigation.

Overall, existing EU food safety frameworks, from novel food authorisations to general food hygiene and traceability regulations, provide oversight for alternative proteins. Continuous research and risk assessment are being encouraged to address any knowledge gaps. With appropriate controls in place, these novel protein sources can meet the same high safety standards that EU consumers expect from traditional foods [29].

CONSUMER ACCEPTANCE

Consumer acceptance remains one of the most significant challenges for alternative proteins. Surveys indicate that European consumers currently have low willingness to consume **insects** as food although 33% of EU respondents stated that they have already tried whole insects or food that contained them [57]. And even insects as animal feed are widely rejected at least as long as no further information are provided [58]. Insect-based foods rank at the bottom in terms of consumer acceptability among protein alternatives. Factors such as strong cultural aversion and limited experience with entomophagy in Western diets contribute to this hesitancy.

Cultured meat also faces scepticism. Many people perceive it as unnatural or are uncertain about its safety and taste, resulting in generally low acceptance levels, only slightly higher than for **insects** in early studies. **Algae-derived** foods (like seaweed or **microalgae** ingredients) are somewhat more accepted, especially in coastal cuisines, but for many European consumers they remain unfamiliar. Attributes such as the sea-like flavour of some macroalgae or the deep green colour of spirulina can be sensory obstacles, meaning **algae-based** products often need culinary adaptation to suit local tastes [29].

By contrast, fermentation-derived protein foods such as **mycoprotein** (e.g. Quorn™) have achieved relatively broad acceptance in Europe over time. These products are usually presented in familiar formats (mince, burgers, fillets) and have a texture and flavour profile that imitates meat, which has helped them gain consumer trust[29]. **Mycoprotein's** long track record on the market and its positioning as a natural, mushroom-like product mean it is no longer viewed as a novel or risky food by most consumers [29].

Looking forward, improving consumer perception is crucial to mainstreaming non-crop proteins. Pricing and convenience will heavily influence adoption. Alternative proteins must be competitively priced and easy to incorporate into everyday meals to overcome inertia. In the short to medium term, hybrid products in which meat or dairy ingredients are partially replaced by plant-based, fungal or other novel proteins are increasingly explored as a pragmatic way to familiarise consumers with new protein sources while maintaining familiar taste and texture, thereby supporting gradual acceptance. Education and marketing can also play a positive role in shaping attitudes. Recent transition-oriented work underlines the importance of coordinated efforts involving food producers, retailers and consumer organisations to raise awareness and improve product attractiveness and points to a long-term vision in which what is considered "alternative" today becomes the default choice, with meat and dairy playing a more supplementary role in diets [26].

SUSTAINABILITY

A major driver behind interest in alternative protein sources is their potential for environmental sustainability. Most non-crop proteins have a substantially lower resource footprint than traditional animal proteins. Farming **insects** or cultivating **microalgae** requires far less land and water per unit of protein produced than rearing livestock and can partially utilise waste or by-product streams as inputs. Life-cycle assessments have found that **mycoprotein** production generates significantly lower greenhouse gas (GHG) emissions than beef production and also lower emissions than poultry production[29].

Insect rearing for protein emits fewer GHG emissions than pig or cattle farming and ammonia emissions are minimal. Importantly, **insects** can be fed on bio-waste, such as vegetable scraps or agri-food by-products, recycling nutrients that would otherwise be lost. However, strict food law requirements must be observed (EG No. 178/2002, article 17/1). **Algae** cultivation, especially if done in open-water seaweed farms or closed-loop systems, can even have restorative environmental effects, such as absorbing CO_2 and nutrients from water, although energy is needed for processing harvested biomass[29].

Cultured meat has the advantage of eliminating manure management and enteric methane emissions. Its land use is projected to be much lower than that of beef cattle, since no grazing or feed-crop acreage is required to grow cells. However, current cultured meat prototypes are energy-intensive. If the electricity used is not from renewable sources, the climate benefit could be negated. Thus, realising the full sustainability gains of **cultured meat** will depend on coupling the technology with clean energy and efficient production methods [29].

Increasing Europe's reliance on these alternative proteins could also yield broader sustainability and food security benefits. The EU today imports around 19 million tonnes of plant proteins (mainly soybean meal for feed) to meet its needs [14]. Developing domestic alternatives helps reduce this import dependence and the associated environmental impacts abroad, such as deforestation and habitat conversion in soybean-exporting countries [15].

According to a recent JRC analysis, a comprehensive strategy combining demand-side shifts, such as more plant-based and novel proteins in European diets, with supply-side measures, such as incentives for local protein crop cultivation and alternative protein production, could cut the EU's agricultural GHG emissions and land use while lowering reliance on imported feed [15]. Diversifying protein sources in EU agriculture, for both food and feed, is seen as a way to improve resilience against shocks. If livestock feed can come from **insects**, fermented **single-cell protein**, or **algae** in addition to crops, the system is less vulnerable to poor harvests or trade disruptions [21].

As part of a circular economy approach, alternative proteins can valorise waste. **Insects** can upcycle organic waste into feed and **microbial protein** can be grown on residual biomass or even industrial gases, closing nutrient loops[29]. By integrating such systems, Europe can move towards a more climate-friendly protein model that aligns with its Green Deal objectives. Policymakers already recognise this opportunity. The European Commission's strategic vision for agriculture explicitly calls for a "more self-sufficient and sustainable EU protein system", highlighting the role of novel protein sources in achieving that goal[4].

Europe's exploration of alternative non-crop protein sources, from **insects** and **algae** to **fermentation-derived** and **cell-cultured proteins**, reveals significant potential to diversify and strengthen the protein supply. These novel sources can deliver high-quality nutrition and carry a lighter environmental footprint, helping to mitigate climate and land-use impacts while reducing dependence on imported protein feeds[29].

At the same time, substantial challenges must be addressed before their benefits can be fully realised. Scaling up production in a cost-effective way is paramount, as many technologies are still emerging from pilot scale and investment in innovation and infrastructure will be required to achieve competitiveness with conventional proteins. Robust safety assessment and regulation will also continue to be essential to ensure that consumers have confidence in these new foods [4].

Perhaps the most complex challenge is consumer acceptance, overcoming cultural biases and convincing a broad base of consumers to regularly include **insect, algae, fungal** or **cultured derived foods** in their diets will likely take time and concerted effort. Targeted policies and support measures can help on all these fronts. Particular emphasis must be placed on consumer communication in order to reduce uncertainty or even rejection. The European Commission has announced plans for a comprehensive protein strategy that integrates alternative proteins into the EU's agricultural and food policy framework, aiming to support innovation, address regulatory barriers and encourage market development [4].

Likewise, EU-funded collaboration platforms on alternative proteins are working on concrete, practice-oriented solutions to normalise these novel sources. One example is the Horizon4Proteins collaboration, which brings together several EU-funded projects on alternative proteins to jointly address consumer acceptance, safety and regulatory challenges, food applications and sustainability. Through shared communication activities, joint policy inputs and the development of practical guidance for industry and other stakeholders, such platforms aim to make new protein sources more familiar, trustworthy and easy to use in real-world settings. As these coordinated efforts progress, what are considered "alternative" proteins today could become a mainstream component of European diets in the coming decades, supporting a more sustainable, secure and resilient food system for the future.

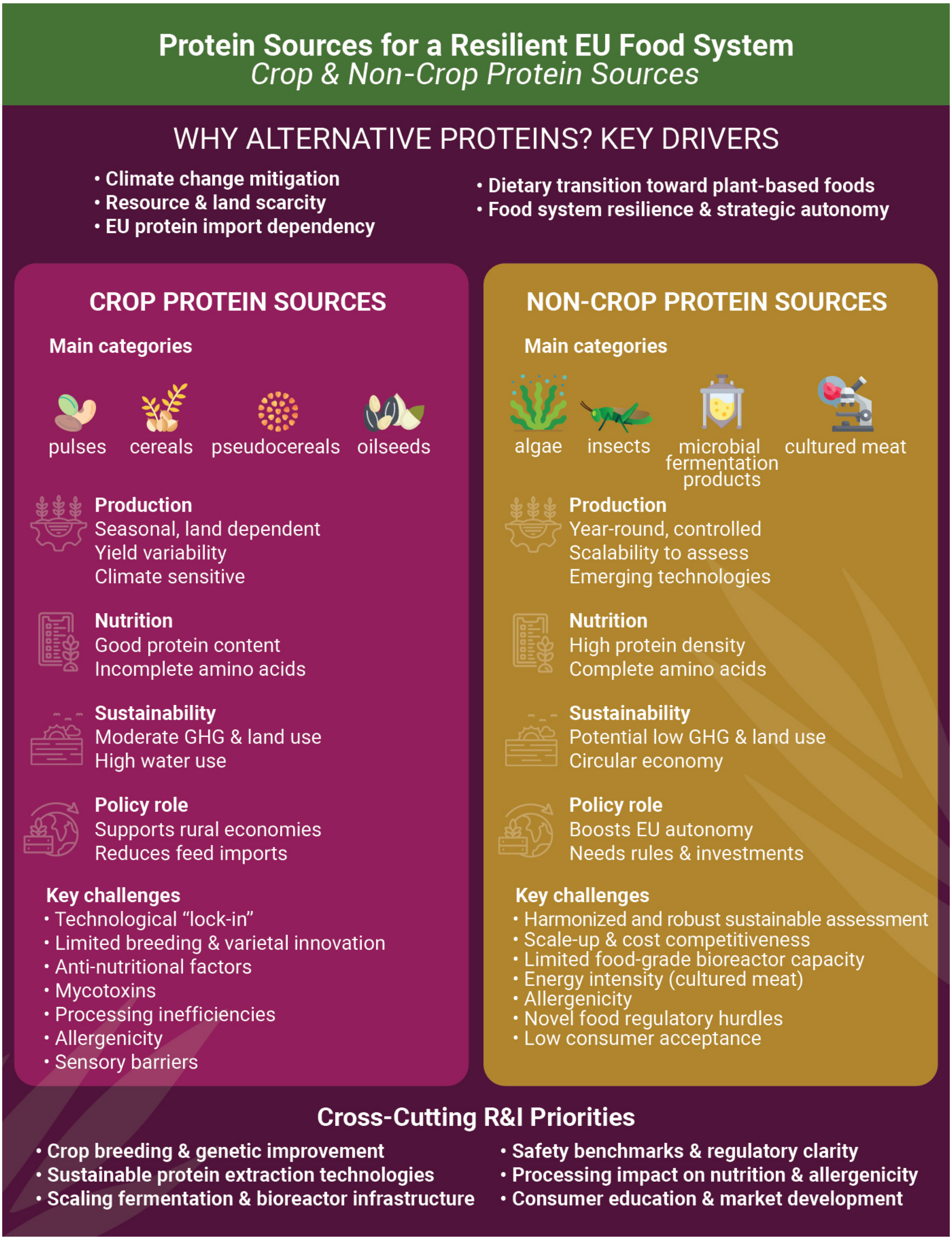

Figure 5. State-of-the-Art on R&I for Alternative protein sources in Europe

3.3. Recap on EU funding projects (Portfolio Analysis summary outcome)

In parallel with the TF's internal analysis work for defining the State of the art on R&I for alternative protein sources, a Portfolio Analysis (PA) of projects has been carried out by external experts with the valuable support of the RefreSCAR project. **The objective of the PA was to identify EU funded R&I projects (in progress or completed within the last 5 years) concerning alternative proteins for food and feed** and highlight **knowledge gaps and overlaps** in the funded projects, thereby outlining the future needs.

The different **protein groups included** were plant-based proteins derived from crops such as legumes (e.g. soy, peas, beans, alfalfa), oilseeds (e.g. rapeseed, sunflower) and cereals, and/or associated by-products such as oilseed meals or by-products from the starch industry, microbial proteins (proteins or protein-rich biomass from bacteria, yeast, microalgae and fungi, including proteins obtained from precision fermentation), insects (such as meal worms and black soldier fly larvae) and cultured meat. Ten projects were **selected for in depth analysis based on thematic relevance** (e.g. protein source, food/feed application) and availability and accessibility of project outputs.

Together, these ten projects form a broad, **complimentary portfolio across the alternative protein sector**, covering the different sources of Single-Cell Protein (SCP) (microalgae, fungi and bacteria), bioconversion/fermentation, insects, legumes, macroalgae, side-stream valorization and cultivated/bioprinted living materials (cultured meat). All ten projects include some form of protein processing and product prototyping, developing either food or feed applications and performing consumer acceptance tests or animal feeding trials. The majority of the projects primarily focuses on process optimization, addressing cultivation and/or protein processing/extraction and product prototyping, with the goal of overcoming challenges such as economic viability and scalability. The remaining projects place a stronger emphasis on building consumer trust and acceptance, aiming to promote mainstream adaption of alternative proteins, although they also involve optimizing protein processing and product prototyping. These projects span **the full value chain from primary production to product prototyping**, with many also incorporating regulatory considerations with strong emphasis on sustainability, circular economy of protein production and life cycle assessment. For more details on the selected projects, the full PA report can be consulted in the SCAR website.

Each of the projects bring unique perspectives, however **several common gaps and challenges** were also identified. The main identified challenges are related to: primary production (e.g. producing protein rich crops and novel biomass streams, inconsistent feedstock, lack of infrastructure); downstream processing for food and feed applications (e.g. scaling and process optimization issues, cost competitiveness); food product development (e.g. sensory and functionality constraints, product formulation and safety challenges, price); feed product development (f.e. digestibility, long-term animal health and performance impact, safety); consumer acceptance (e.g. sensory issues, 'processed' perception, cultural appropriateness, misinformation, product availability); sustainability (e.g. methodology inconsistency, energy consumption, limited data, economic and social sustainability); regulatory bottlenecks (e.g. complexity and cost for approval, labelling and terminology) and policy bottlenecks (e.g. support and stimulation tools, value chain development).

The TRLs of most of these projects range from TRL 4-5 to TRL 6–7. This, together with the mentioned gaps and challenges above, **emphasizes the need for more fundamental science on specific challenges in the value chain**, to better understand the fundamental mechanisms driving these gaps and challenges and to be able to facilitate targeted solutions.

Cross-cutting recommendations to accelerate the sustainable adoption of alternative proteins across Europe can be formulated as: integration of the value chain to bridge supply and demand gaps; development of integrated transition pathways (agronomy, genetics, socio-economic context) in different EU-climatic zones; increase farmer engagement, training and education; more investing and funding tools for scale-up regarding downstream processing; improve (mild) processing technologies; improved food and feed formulations; enhance consumer-centric innovation; invest in consumer education and broader food product diffusion; a holistic and integrated sustainability evaluation; foster harmonized regulation and policy alignment; invest in economic viability; support collaborative platforms and shared data resources.

4. CHALLENGES, OPPORTUNITIES & POTENTIAL ACTIONS for R&I

Towards strategic autonomy and sustainability through the protein value chain in EU

Across Europe, many research initiatives now frame protein diversification within food systems or transdisciplinary perspectives, in line with the Food 2030 policy agenda that calls for integrated R&I to deliver sustainable, healthy and resilient food systems. Yet, true **scientific integration remains limited**. Most projects connect actors and disciplines at the application level but rarely achieve **deep convergence across scientific domains.**

The following section analyses the **whole protein value** chain with the aim to identify the **key disciplinary questions** that remain to be addressed in order to support the **transition** towards sustainable and **diversified protein systems.** With this purpose, the protein value chain has been broken down into each of its different stages or nodes for a detailed analysis. It includes:

- An initial section dedicated to Primary Production.
- A section addressing protein for Feed, with the following stages: Processing & Storage; Distribution & retailing and Animal Nutrition.
- A section addressing protein for Food, with the following stages: Processing & Product development; Distribution, retailing and value chain structure and Consumption, consumer acceptance, nutrition.
- A joint section dedicated to End of Chain, Waste and Circularity.
- A common Cross-Cutting section at the Scale of the Entire Value Chain and at the Feed-Food Interface.

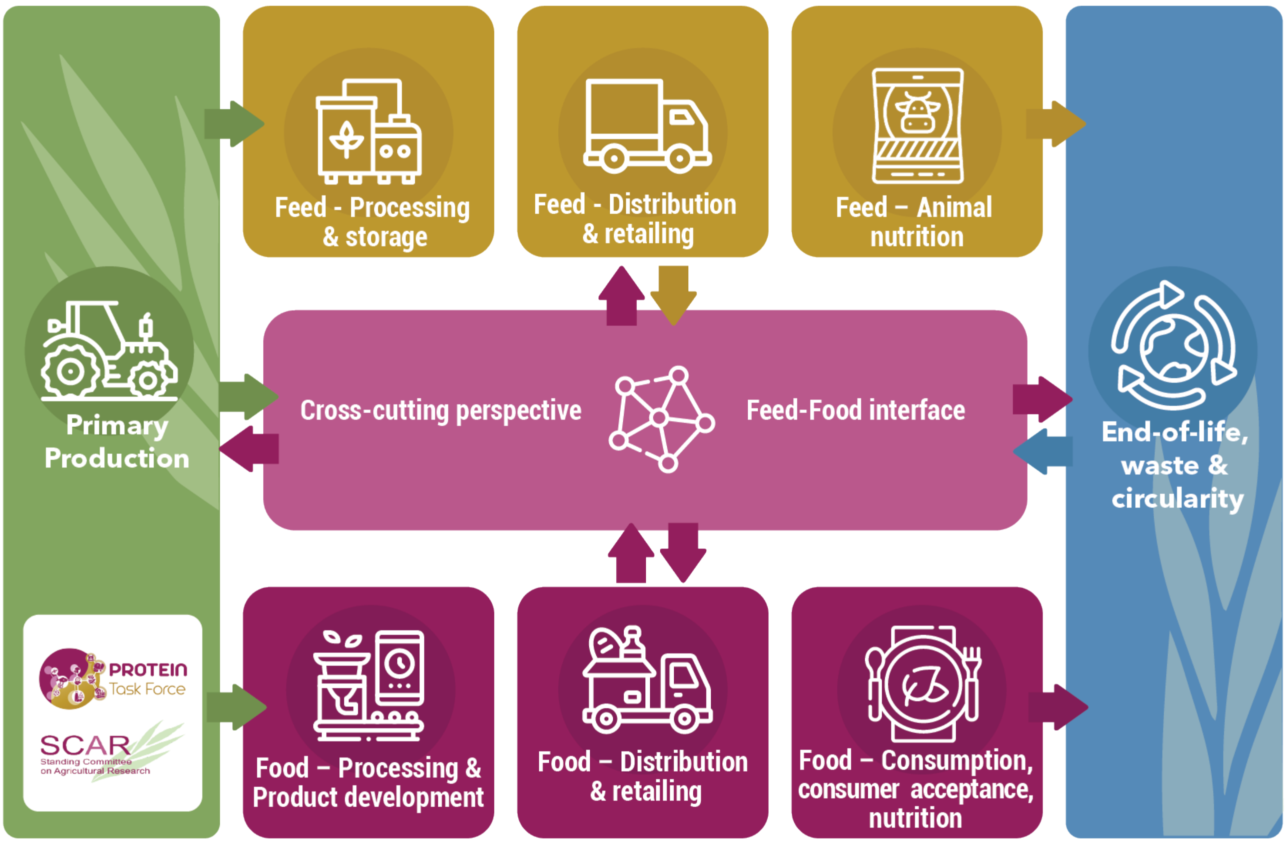

Figure 6. Protein Value Chain approach taken by the SCAR Protein TF for analysis of the alternative protein sources towards strategic autonomy and sustainability in EU

4.1. Primary Production

Primary production strongly conditions not only the availability of protein resources but also their nutritional quality, environmental footprint and value in agricultural and food systems, in interaction with processing and consumption patterns. In line with the *Green Deal, the Farm to Fork Strategy* and the *EU Protein Plan*, **diversification of protein crops represents a key lever to strengthen the EU resilience and autonomy**.

Introducing or revalorising crops such as sorghum, millet, pseudo-cereals (e.g. quinoa, amaranth), oilseeds (e.g. camelina, flax, hemp) and grain legumes (e.g. beans, peas, lupin, chickpeas, soy) or forage legumes (e.g. alfalfa, red and white clover) offers multiple agronomic and strategic advantages. Some of these species are relatively drought-tolerant and suitable for marginal lands, with lower input requirements [59,60]. Legumes, in particular, play a central role by fixing atmospheric nitrogen, reducing fertiliser dependence and contributing to soil and ecosystem health. Integrating such species into rotations supports agroecological practices that enhance soil health and biodiversity, reduces pest pressure and enhances the stability and resilience of European farming systems.

Despite these well-recognised benefits, large-scale deployment of diversified protein crops in Europe remains limited. Scientific, structural and economic challenges persist. Many underutilised crops have historically received **limited and inconsistent breeding investment** [61], resulting in significant **gaps in genetic improvement compared with major cereals and oilseeds**. Yields of many alternative crops remain low and/or unstable, particularly under increasing climate variability and extreme weather events. Moreover, breeding efforts have traditionally focused on a narrow set of traits, mainly yield and disease resistance, with limited attention to the nutritional properties and processability of these crops [62]. Future breeding programme should therefore aim at **multi-criteria improvement: enhancing yield stability, climate resilience, nutritional quality and pest tolerance, while maintaining genetic**

diversity. At the same time, breeding programme need to incorporate end-use requirements, both for feed and food, including traits relevant to processing (e.g. dehulling, cooking, milling) and the reduction of anti-nutritional factors (e.g. phytic acid, tannins) that impact digestibility or industrial valorisation. **Strengthening links between breeding, post-harvest processes and downstream value chains is essential, as processing quality increasingly shapes both market competitiveness and consumer acceptance.**

Since the performance of improved varieties emerges from interactions between genotype, environment and agronomic management, enhancing the competitiveness of European protein production also requires **agroecological innovation and the co-design of agronomic practices tailored to local contexts.** Many crops require adapted technical itineraries, including optimised sowing dates, plant densities, crop associations and soil–plant–microbe management, which are not yet well established across European pedoclimatic conditions. **Knowledge gaps remain substantial, especially regarding crop performance under low-input or variable climatic contexts and the limited availability of regionally adapted guidelines restricts farmer adoption.** Farmers frequently report uncertainties about managing these emerging crops in specific rotations and environments and often lack practical information to adjust fertiliser, pesticide or tillage practices accordingly [63–65]. Recent studies indicate that **participatory, practice-oriented research conducted in close collaboration with farmers** and involving agricultural advisors, as key innovation intermediaries, helps generate effective, locally adapted solutions [66].

Recent advances in **agroclimatic modelling, earth observation and data-driven analytics** have significantly **improved the capacity to anticipate crop performance under changing climatic conditions** and to **guide spatial planning** for protein crop expansion. For instance, simulation studies on sorghum indicate that this drought-tolerant crop could experience yield gains in several European regions by 2100 [33], while projections for soybean suggest that Europe could approach greater levels of self-sufficiency if agroclimatic conditions, cultivated areas and management practices were optimised [67]. However, for many legumes and underutilised protein crops, **agronomic and performance data remain fragmented** [68], limiting the ability to build robust, spatially explicit development scenarios and support evidence-based policy design. **Strengthening European observatories and interoperable data infrastructures on protein crops, would facilitate the integration of experimental, climatic and market data into predictive models and territorial planning tools.**

Potential Actions:

- **Support multi-criteria breeding programme that combine genetic improvement for yield stability, climate resilience, nutritional quality, processability and lower anti-nutritional factors with data-driven approaches.** This requires reinforcing **integrated fundamental and translational research** to unravel the multi-scale mechanisms, from gene regulation and metabolic pathways to whole-plant physiology and field performance, that underpin productivity, resilience and key agronomic and quality traits relevant to diversified protein crops. Such efforts should be closely connected with downstream processing requirements and nutritional objectives to ensure coherent improvements across the entire value chain.
- **Develop and scale context-specific agroecological practices by strengthening territorial innovation ecosystems that combine Living Labs, multi-actor networks and demonstration farms.** This requires linking on-farm experimentation with digital tools for data collection and modelling to generate robust, transferable evidence across pedoclimatic regions. By embedding agronomic innovation within participatory research infrastructures, aligned with initiatives such as the EU Mission *A Soil Deal for Europe*, these systems can enhance cross-regional learning, reinforce farmer engagement and accelerate the adoption of diversified protein cropping systems. Integrating socio-economic analysis, advisory services and value-chain coordination into these territorial ecosystems will be essential to ensure durable transitions.
- **Reinforce European data infrastructures and observatories to close knowledge gaps in agronomic, environmental and performance data for legumes and underutilised crops, enabling robust predictive modelling and evidence-based policymaking.** This requires strengthening

coordinated monitoring networks, integrating **field-level measurements with soil, climate and management data** [69] and **developing interoperable, open-access platforms capable of capturing spatial** [70] **and temporal variability across regions**. Such comprehensive data systems are essential to support advanced predictive modelling, improve the transferability of crop suitability and yield forecasts and provide a robust evidence base for designing targeted policies and R&I strategies that accelerate the deployment of diversified protein cropping systems.

4.2. Feed - Value Chain Stages

4.2.1. Processing & Storage

Feed supplies are crucial elements of livestock production systems and their effective utilisation is the principal factor influencing animal performance and productivity. The accessibility and utilisation of local feedstuffs, encompassing novel and underutilised sources, particularly alternative protein sources such as insect meal (Processed Animal Proteins - PAPs), pose challenges in numerous livestock farming systems, with significant consequences for farm economics, product quality and safety, as well as animal health and wellbeing. Moreover, it is essential to develop more accurate and robust feeding systems while safeguarding the criteria for biodiversity protection and restoration.

Developing new, regionally available feedstuffs focuses on using novel feed resources like agricultural by-products (from milling, sugar and oil processing), local weeds, native plants, green biomass food processing residues [71] and insect larvae reared on approved vegetal substrates to reduce reliance on imports, lower costs and promote sustainable agriculture. This opportunity involves identifying nutritional value, processing methods and optimal inclusion rates for livestock, while considering socio-economic factors and potential anti-nutritional factors to enhance farm circularity and food security.

Nutritional quality and safety of plant-based and insect-based protein sources for animal feed should be improved. This involves reducing anti-nutritional compounds through better processing, creating species- and life-stage-specific formulations and developing modular, low-cost processing systems for local production. Advanced techniques like protein fractionation, fermentation, mechanical extraction of insect lipids and functional processing can enhance digestibility, palatability and product value. Additional priorities include improving shelf life, packaging and traceability, as well as implementing rigorous quality control and mycotoxin screening. End-to-end recommendations cover raw material handling, processing steps (such as dehulling, milling, thermal treatment, drying/rendering of insects and biochemical upgrades), storage conditions and compliance with feed safety standards.

Potential Actions:

- **Support cost-effective processing solutions for regional feedstocks.** Develop and invest in low-tech, modular technologies (e.g., solar drying, mobile pelletisers, fermentation units) accessible to cooperatives and SMEs. These solutions enable local actors to process agricultural by-products and insect-based feeds efficiently, reducing dependency on imports and improving circularity.
- **Develop treatment protocols to reduce Anti-Nutritional Factors (ANFs).** Combine breeding for low-ANF varieties with processing techniques (thermal, enzymatic, fermentation) to improve feed safety and performance. Integrated approaches ensure higher digestibility and nutrient availability, enhancing animal health and productivity.
- **Enhance data on composition and performance.** Create open-access nutritional databases and conduct field trials to support precision feed formulation and decision-making. Reliable data on nutrient profiles and performance outcomes allows farmers and nutritionists to optimise feed mixes for different species and life stages.
- **Foster structured networks between nutritionists and agro-industry.** Encourage collaboration through Living Labs, pilot projects and advisory platforms to bridge knowledge gaps. Collaborative platforms can also support training and capacity building for SMEs.
- **Promote circular feed inclusion in national protein strategies.** Align livestock and crop systems under One Health and climate-smart agriculture frameworks to support systemic sustainability. This alignment ensures that feed innovation supports broader sustainability objectives.

4.2.2. Distribution & retailing

The distribution and retailing phases are pivotal in the feed value chain, concentrating on transferring the completed animal feed product from the producer to the final consumers, including farmers and aquaculture facilities. This phase enhances value by guaranteeing the prompt, efficient and quality-preserving distribution of the feed. Distribution and retailing of feed materials are essential for making new proteins widely available and successful.

Reduction of feed waste (which cannot be precisely quantified at the moment) through short supply chains is also of high importance: an improved coordination can prevent spoilage of high-moisture or perishable feed resources. The use of novel feedstuffs will increase the diversification of animal diets, which is especially relevant for the organic and low-input livestock sector where protein sourcing is limited.

Digital platforms for by-product matching and logistics can provide real-time tools that connect food industries with livestock and insect producers based on geography, volume and feed value. Symbiotic relationships between local processors and farms will reduce transport costs and emissions. Farmer cooperatives and regional feed hubs can pool transport and processing for efficiency.

Insect farming acts as a unique driver of circularity within this framework, acting as a bio-converter that upcycles authorised low-value vegetal by-products and former foodstuffs into high-quality nutrients. This process not only reduces food waste but also closes nutrient cycles, as the resulting insect excrement serves as a valuable organic fertiliser, returning nitrogen and phosphorus to the soil.

However, at the moment there seems to be limited awareness of available alternative feedstuffs. By-products from food processors (e.g. peels, spent grains, pulp) are often not visible or accessible to livestock feed producers or insect farmers. There is a lack of coordinated platforms to facilitate resource sharing, traceability and value chain integration at regional level. Besides, there is insufficient information on storability and logistics of new feed materials. Wet or structurally unstable materials (e.g. segregation, compaction) pose hygienic and storage risks if not handled promptly.

Existing distribution chains are often inflexible and centralised. Small-scale or decentralised actors have difficulty in accessing or integrating circular feed resources into existing logistics networks. In addition, there might be a mismatch between feed production timing and demand, as seasonality and perishability of feed by-products create bottlenecks in consistent supply. However, the localised circular economies promoted by insect farming facilitate connections among territorial stakeholders. Insects, particularly species like *Hermetia illucens*, are capable of utilising residues and by-products that cannot be used by humans or other farm animals. In this way, they do not enter into competition with anyone. Moreover, insect farming, being an indoor controlled system, can offer a year-round constant supply, mitigating some of these seasonal bottlenecks.

Potential Actions:

- **Foster regional collaboration between food, feed and farming sectors.** This requires creating mechanisms for knowledge sharing and trust-building through multi-actor networks, matchmaking events and shared logistics or regional distribution hubs. Such coordination will ensure timely access to feed of adequate quality, reducing inefficiencies and strengthening resilience across the supply chain
- **Develop decision-support tools for feed supply chain optimisation.** This requires integrating seasonality, perishability and storage profiles into regional planning and distribution systems. Advanced modelling and digital platforms can enable predictive logistics, minimise waste and improve cost-efficiency, supporting a more sustainable and responsive feed network.
- **Invest in infrastructure for local collection, pre-treatment and delivery.** This requires deploying cold chains, anaerobic storage, mobile pressing/drying units adapted to specific by-products and rapid screening facilities for feed quality within distribution networks. Such investments will enhance feed safety, reduce losses and enable flexible processing close to production sites.

- **Promote transparency and traceability in circular feed flows.** This requires implementing feed origin labelling and quality protocols for novel inputs, supported by interoperable digital systems. Greater transparency will build trust among stakeholders, encourage adoption of innovative feed sources and ensure compliance with sustainability standards.
- **Integrate circular feed logistics into protein and rural development strategies.** This requires embedding localised feed chains within broader food security, climate mitigation and regional resilience frameworks. Aligning these strategies will reinforce synergies between protein diversification and rural economic development, accelerating systemic transitions.
- **Support regional interactions between farmers, food and feed producers.** This requires strengthening collaborative platforms and advisory services to enable faster, more efficient supply chains. Enhanced coordination will reduce transaction costs, improve resource utilisation and foster innovation across the feed sector.

4.2.3. Animal Nutrition

The animal nutrition and feed industry face significant challenges alongside unique opportunities. Meeting the twin challenges of sustainability and productivity requires a holistic strategy that integrates technological innovation, resource efficiency and strict compliance with regulations. Embracing trends such as precision nutrition, alternative proteins and digital transformation enables the industry to effectively navigate its challenges. The feed industry must adapt to evolving consumer expectations while prioritizing advancements in animal health, environmental stewardship and economic resilience. The future of animal nutrition is rooted in sustainable, science-based solutions that provide advantages for animals, producers and the environment.

Alternative protein sources in animal nutrition are of high relevance, because they present an opportunity to align feeding strategies with circular and climate-smart goals. Imported or high-footprint protein feeds should be replaced by feedstuffs, that are not suitable for human consumption or grown on areas which cannot be used to grow food, will contribute to climate goals contributes to GHG reduction and resilience is possible with alternative protein sources but also require complex approval procedures. Specifically, Processed Animal Proteins derived from farmed insects are currently legally authorised in the EU for use in aquaculture, poultry and pig feed, offering a high-value protein alternative.

Since protein feeds represent a major cost component, more efficient or local alternatives can rapidly be integrated the market, especially because of the large turnover on the feed market. The quality of the used protein source is always of special interest, as animal protein requirements have to be respected. Some novel ingredients, like insect meal, show excellent amino acid balance, fibre profiles and fermentability for ruminants or monogastrics.

In the future, the use of precision feeding and modelling tools will increase. This is in advantage regarding the challenge of integration of variable feedstuffs in complete diets/daily rations (like "new"/alternative feedstuffs) while maintaining animal performance, particularly in digitalised farms increasing the sustainability of animal production.

Upscaling of research results into sectoral guidelines *via* nutritional recommendations should be no hindrance since science-based nutritional recommendations can accelerate safe and widespread adoption of new feeds.

However, there are concerns regarding the possible enhancement of protein crops and the utilisation of alternate protein sources. The huge diversity/variability of protein-rich feedstuffs (esp. the new/under-utilized ones like press cakes, leaf proteins, fermentation residues and insect-derived ingredients) imply current gaps in precise quantification of their effects on animal performance and the quality of products (food) of various species & categories in farm animals. A lack of data on species- and age-specific responses is a risk in modern farming. Effects of alternative proteins on feed conversion, growth, reproduction or product quality (milk, meat, eggs) are poorly characterised across livestock types for alternative protein sources.

An inconsistent quality of protein feed (for example inconsistent nutritional profiles due to seasonality) or insufficient standardised data on digestibility, amino acid profile and feed value is feared as well as a restricted availability of alternative protein feeds, for example due to seasonality, which would be a huge disadvantage especially in high producing animals.

Subsequently, also the presence of antinutritional factors (ANFs) in "new" feedstuffs, including phytic acid, resulting in a reduced nutrient availability (particularly phosphorus and trace minerals), may impair animal performance, if untreated. Same is true for the presence of possible contaminants, which pose a risk for the animals and the products.

Last but not least, the implementation of recommendations, which are based on research results is slow at the moment, limiting adoption in commercial settings.

Potential Actions:

- **Conduct systematic studies on feeding value and side-effects of alternative proteins.** This requires evaluating novel protein feedstuffs across species, production stages and production systems to determine digestibility, intake, productivity and health impacts. Such evidence will help mitigate perceived risks and unlock the positive properties of alternative proteins for sustainable livestock systems.
- **Develop nutritional species-specific databases and decision-support tools.** This requires integrating knowledge about compositional variability of new feedstuffs into digital platforms that enable precise ration formulation. These tools will support farmers and feed manufacturers in optimising diets and improving animal performance while reducing uncertainty.
- **Establish monitoring protocols for seasonal variability and crop performance meta-analysis.** This requires creating quality benchmarks and adjustment rules to ensure daily rations and complete feeds remain consistent throughout the year. By aggregating data across species and regions, these systems will enhance predictability and feed quality management.
- **Address risks of Anti-Nutritional Factors (ANFs) through breeding and processing strategies.** This requires promoting low-ANF and low-phytate genotypes, as well as processing techniques such as enzymatic treatment and fermentation. Disseminating this knowledge to farmers and feed producers will reduce health risks and improve nutrient availability in alternative protein sources.
- **Support translation of research outcomes into validated nutritional guidelines.** This requires collaboration with extension services and feed manufacturers to scale up findings from trials into practice-ready protocols. Embedding this nutrition-livestock-climate approach into feed policy, through sustainability and animal welfare strategies or national protein plans, will accelerate adoption and systemic impact.

4.3. Food - Value Chain Stages

4.3.1. Processing & Product development

Processing plays a pivotal role in determining the nutritional quality, functionality, sensory appeal and sustainability of protein-rich foods. It bridges primary production and product development, shaping how protein crops are transformed into ingredients and foods that meet consumers and environmental expectations. Processing of protein-rich crops, such as legumes, oilseeds and cereals, encompasses a **broad range of operations, from mechanical pre-treatment (e.g. dehulling, milling, sorting) to fractionation (dry, wet or hybrid), ingredient modification (e.g. thermal, enzymatic or fermentation processes), product structuring (e.g. extrusion, gelling, emulsifying) and packaging.** The **selected processing route strongly determines yield, cost and resource use, but also affects nutritional quality** (digestibility, amino acid bioavailability, antinutritional factors), **techno-functional performance** (solubility, water-holding, foaming, emulsification) and **sensory attributes** (colour, flavour, mouthfeel). **Understanding the interactions among these dimensions remains a major scientific challenge for achieving consistent quality and performance across diverse European protein crops.**

Despite significant scientific and technological progress, large-scale industrial uptake of alternative European protein sources remains limited. Over 70 % of legume-based foods still rely on soy and pea [72]. Many underutilised crops offer strong agronomic potential but remain constrained by variable processing performance, limited supply chains and limited supply chain standardisation. **Processability varies widely among and within species**, due to differences in biochemical composition, water activity, cell-wall structure and more generally grain microstructure. Yet the **determinants of processability, like cooking, milling behaviour, dehulling efficiency, extractability and performance during product structuring, remain insufficiently characterised.** High-throughput screening, compositional analytics and multi-scale modeling could help identify predictive markers of process performance and enable data-driven and adaptive process optimisation.

Raw-material variability, resulting from genotype diversity, agroclimatic fluctuations and local growing conditions, further challenges process standardisation and cost efficiency. Unlike globally traded soy or wheat, many emerging European crops exhibit high heterogeneity in composition and processability. **Developing adaptive and flexible processing systems, capable of real-time adjustment via sensor-based controls** (e.g. inline NIR spectroscopy, digital twins, or machine learning), will be crucial to ensure stable quality. Territorial infrastructures for dehulling, pressing, fermentation or roasting are also essential to close gaps in regional protein supply chains. Decentralised processing hubs contribute to regional autonomy, lower transport needs and strengthen local economic resilience.

Protein extraction and modification remain key areas of innovation [73,74]. Dry fractionation (e.g. air classification, electrostatic separation) offers low-energy routes to protein concentrates (50–60% of protein content), while wet extraction (solubilisation, precipitation, membrane filtration) achieves higher purity (up to 90%) but with higher resource intensity [50,75]. Hybrid and cascade processes, combining dry pre-fractionation and mild wet steps, illustrate promising pathways to reduce water and energy use [76]. Emerging techniques such as ultrasound, microwave, or enzyme-assisted extraction enable gentler treatments preserving protein structure and functionality. However, **wider generalisation across crops, scales, yields and purity levels remains to be demonstrated**; also **multi-criteria sustainability assessments, including environmental, techno-economic and social indicators, are needed to guide design-for-sustainability in processing systems.**

Structuring technologies encompass a broad spectrum of physical, chemical and biological processes that transform protein-rich ingredients into foods with specific textures and sensory characteristics. Examples include extrusion, emulsification, gelling and fermentation processes used to tailor texture, stability and sensory quality in alternative protein foods. These processes modify protein folding, aggregation and interfacial activity, mechanisms that govern gelling behavior, water-holding capacity and overall textural performance. They also induce a range of chemical reactions, such as Maillard reactions and oxidation, which further influence color, flavor and nutritional value. **Understanding structure–function–nutrition relationships across molecular to macroscopic scales remains a key scientific frontier for ensuring consistency, quality and consumer appeal.**

Beyond isolates and concentrates, **whole-grain and semi-processed approaches**, based on milling, soaking, cooking, germination or fermentation, offer **complementary pathways that preserve dietary fibres, minerals and bioactive compounds**. Such approaches expand the diversity of protein-rich ingredients suitable for both industrial and domestic applications. These approaches may maintain certain antinutritional compounds (e.g. phytates, tannins) or generate sensory challenges (colour, astringency, bitterness) requiring additional pre-treatment or formulation strategies. **Optimising the degree of processing according to crop composition**, favouring whole-grain or semi-processed routes where feasible and refined fractionation when necessary (e.g. valorisation of oilseed meal) **will therefore be essential to balance nutritional, functional and sustainability objectives across European protein value chains**.

Potential Actions:

- **Develop high-throughput analytical and screening tools.** Systematic assessment of processability at grain, flour and protein ingredient levels should identify key physicochemical determinants (e.g. for dehulling, solubility, foaming, gelling, water-holding), enabling data-driven optimisation of processing routes.
- **Invest in territorial processing and logistics infrastructures.** Reinforce regional capacities for harvesting, sorting, storage and primary transformation of emerging crops to reduce transport impacts.
- **Advance predictive and integrative research on structure–function–nutrition relationships.** Support multi-scale studies linking raw material composition, biochemical reactivity, microstructure and functionality to accelerate the design of high-performance, health-aligned and environmentally optimised plant-based food.
- **Promote flexible, adaptive and resource-efficient processing systems.** Deploy sensor-integrated and AI-assisted process control to handle variability in crop composition and ensure consistent product quality across regions.
- **Strengthen pilot plants and open-access scale-up infrastructures.** SMEs and start-ups developing protein processing innovations face major barriers in upscaling technologies and overcoming the "valley of death." Dedicated pilot lines, shared facilities and innovation hubs should be established or reinforced to de-risk industrial deployment.

4.3.2. Distribution, retailing and value chain structure

Distribution and retailing are critical connectors between upstream innovation and consumer behaviour. They represent key nodes in the socio-technical organisation of food systems, shaping how technological and organisational innovations translate into market transitions and societal change.

Retailers, catering services and public procurement actors influence the visibility, accessibility and acceptance of alternative proteins [77,78]. Through assortment, pricing and product placement, they structure food environments and determine exposure to new products. Evidence shows that **increased availability and favourable presentation substantially enhance trial and adoption of plant-based foods [78,79]. Public procurement, guided by EU and national sustainability criteria, can act as a powerful lever for the protein transition** by directing demand toward sustainable and regionally sourced protein products [80].

However, European protein value chains remain fragmented. Midstream capacities (storage, primary processing, logistics) are often insufficient, leading to inconsistent volumes and quality [23,82]. Long-standing coordination challenges, weak vertical linkages, limited contracting and missing aggregation platforms, hinder scaling and investment [31,83,84]. Addressing these requires **systemic and territorial governance models that connect production, processing, logistics and retail actors under shared sustainability objectives.** Concepts such as protein corridors, regional hubs and multi-actor innovation platforms (e.g. DIVINFOOD, SUSINCHAIN) exemplify this approach by aligning technological innovation with organisational coordination.

Digitalisation plays a growing role in this transformation. Value-chain digital twins, blockchain traceability and data-sharing infrastructures can enhance transparency, logistics efficiency and performance monitoring. By embedding sustainability and nutritional indicators (e.g. PDCAAS/DIAAS, carbon footprint, origin) in labelling and procurement, policymakers can operationalise science-based criteria and accelerate market harmonisation.

Potential Actions:

- **Establish territorial pilot projects and integrated regional value chains to test logistics, economic viability and food-loss reduction.** Regional pilots can connect producers, processors and retailers to improve storage, transport and aggregation. These projects help identify bottlenecks, reduce waste and create scalable models for sustainable protein supply chains.
- **Harmonise EU labelling and regulatory frameworks, integrating nutritional and environmental performance indicators.** Unified labelling with metrics like protein quality, carbon footprint and origin would simplify consumer choices, support public procurement and incentivise sustainable practices across borders.
- **Develop digital decision-support tools (e.g., digital twins, value-chain simulations) to optimise logistics and governance.** Digital twins and blockchain traceability can simulate supply chain scenarios, improve coordination and enhance transparency, enabling data-driven decisions for efficiency and sustainability.
- **Address socio-technical lock-ins through coordinated policy reforms aligning incentives, institutional frameworks and innovation support.** Reforms should tackle entrenched systems by offering financial incentives, updating food safety standards and fostering multi-actor platforms to accelerate adoption of alternative proteins.

4.3.3. Consumption, consumer acceptance, nutrition

Plant-based proteins, including pulses and plant-based meat analogues, emerge as the most promising category of alternative proteins in terms of acceptance, largely because they are already more familiar to consumers than insects, algae, or cultured meat [85]. Yet acceptance is still insufficient to drive large-scale dietary change. Adoption is limited by a combination of sensory, psychological and social factors [85]. Suboptimal taste and texture continue to reduce appeal, while pulses suffer from low culinary familiarity and perceived inconvenience. **These product-related issues interact with broader psychological and social barriers**, including reluctance to try unfamiliar foods, strong emotional attachments to meat and negative experiences with early plant-based products. Social norms also remain unfavourable: in many high-meat households, plant-forward meals are not yet seen as routine or desirable [85]. Moreover, plant-based analogues are often perceived as "highly processed," even when this is not accurate [86], which reduces trust and willingness to try. Added to this is a lack of ideas or even skills when it comes to preparing these products.

Information-based interventions alone have demonstrated limited effects on behaviour [87]. Although they can increase awareness, their impact on actual food choices remains modest unless combined with structural and sensory changes in the food environment. Future research should therefore prioritise the **behavioural, sensory and contextual drivers of food choice**, recognising that decisions around plant-based food are shaped by a combination of habit, affective responses, social identity, convenience and cultural expectations. Complementing these efforts with **longitudinal purchasing data** is needed for capturing **actual behavioural change and understanding variations across socio-economic groups, household types, time constraints and regional culinary traditions** [88]. In parallel, it is important to recognise the **role of culinary professionals,** including chefs, in shaping food environments: they can act as influential intermediaries by creating appealing plant-based dishes and showcasing new uses for plant proteins, thereby helping innovations gain everyday relevance [89–91].

Beyond consumer perceptions, product development must address technical challenges related to how ingredients and technologies shape nutritional quality, safety and allergenic risk. Some plant-based analogues contain elevated sodium levels, multiple additives or suboptimal protein quality [92], raising questions concerns about their **nutritional benefit and long-term health implications** [93,94]. Addressing these issues requires **systematic evaluation of formulation strategies, ingredient functionality and their consequences for nutritional and health properties. Allergenicity** represents an additional scientific challenge. The diversification of protein sources introduces **novel or poorly characterised proteins whose allergenic potential cannot be fully inferred from existing datasets.** Structural similarity to known allergens carries the **risk of cross-reactivity in allergic patients** [95–97], while no validated methods are available to evaluate the **risk of *de novo* allergic sensitisation**. Lastly, transformation processes such as heating, extrusion or fermentation may modulate allergenicity [98,99]. Given these uncertainties, there is a need for **reliable** and **standardised allergenicity assessment** integrating *in silico* prediction, cross-reactivity assessment, analysis of epitope structural features, digestibility, *in vitro* screening models mimicking the molecular mechanisms of allergy and the assessment of food-processing–induced changes. In addition, a better understanding of sensitisation mechanisms is required to ultimately improve the **evaluation and prediction of the allergenic risk of new protein sources**.

From a broader food-systems perspective, hybrid products blending plant and dairy [100], egg or meat proteins offer a promising route to improve amino acid balance, functional quality and consumer acceptance without requiring abrupt dietary shifts. Such products may also support regional protein autonomy by creating steady demand for European-grown legumes and by providing **opportunities for dairy- or meat-producing regions**. Important knowledge gaps remain. Expected benefits such as improved digestibility, reduced off-flavours and better palatability still require robust evidence.

Potential Actions:

- **Advance behavioural and sensory research to understand the drivers of acceptance of alternative proteins.** This requires interdisciplinary work combining behavioural science, sensory analysis and real-world trials in canteens, retail and online environments to identify effective levers such as repeated exposure, tasting opportunities, pricing and environmental cues, supported by longitudinal purchasing data.
- **Strengthen R&I on formulation and processing to enhance sensory quality and nutritional performance.** Focused research is needed on how processing conditions, ingredient interactions and structuring technologies affect flavour, texture and nutritional properties to develop products that are both appealing and nutritionally robust.
- **Develop harmonised allergenicity assessment frameworks for emerging proteins.** Coordinated evaluation of allergenicity is required to ensure safety and regulatory coherence as the diversity of proteins increases.
- **Support innovation in hybrid products combining animal and alternative proteins.** Research should clarify how protein-protein interactions and processing influence functional properties, palatability and nutritional balance, enabling hybrids that improve acceptance while strengthening demand for EU-grown legumes.
- **Integrate culinary innovation into protein transitions.** Collaboration with chefs and food-service professionals is needed to develop appealing applications for plant proteins, increase familiarity and shift social norms around plant-forward meals.
- **Strengthen social knowledge and literacy for plant-based protein sources**. Children and adolescents are still developing their future eating habits and are therefore often more open to new products. They also act as multipliers within their families. If, for example, they receive information at school about the need to change their eating habits or are served meals based on plant-based proteins, this can also lead to changes within their families.

4.4. End-of-chain, waste and circularity

End-of-chain stages in protein value chains represent a critical leverage point for achieving the EU's objectives on resource efficiency, climate neutrality and strategic autonomy. Advancing circularity within the European protein system requires not only technological innovation but also integrated governance that connects primary production, feed and food processing, waste management and regional planning under coherent bioeconomy frameworks.

Closing nutrient loops remains a cornerstone of circular protein systems. Safe manure and co-product processing (anaerobic digestion, composting, separation, precision fertilisation using frass) can recover nutrients, reduce greenhouse and ammonia emissions and produce renewable fertilisers. However, regional imbalances in livestock density and insufficient nutrient monitoring continue to limit operational circularity at the territorial level. In addition, environmental risks linked to manure mismanagement can appear. Over-application or poor handling contributes to water and air pollution (e.g. nitrate leaching, ammonia emissions).

Strengthening the integration of crop–livestock–food systems within territorial circular bioeconomies is crucial. Regional coordination mechanisms can optimise flows of nutrients, co-products, energy and information across farms, cooperatives, processors and waste-handling actors. Cross-sectoral collaborations with the food industry are especially important since feed production heavily relies on by-products such as protein-rich residues, starch side-streams, oilseed press cakes or fermentation biomass. Embedding processing and product development in shared biorefinery platforms, co-designed with farmers, SMEs and regional authorities, would enable more efficient cascading uses of biomass while reinforcing economic resilience and social acceptance. Across all cascading pathways, food applications should remain the priority use. End-of-chain stages in protein value chains represent a critical leverage point for achieving the EU's objectives on resource efficiency, climate neutrality and strategic autonomy. Advancing circularity within the European protein system requires not only technological innovation but also integrated governance that connects primary production, feed and food processing, waste management and regional planning under coherent bioeconomy frameworks.

Technological innovation in enzymatic, microbial and fermentation-based valorisation can upgrade diverse side streams into food- and feed-grade ingredients, supporting the emergence of new circular protein streams such as leaf proteins, fibre fractions, microbial biomass or tailored hydrolysates. Yet the scaling of such technologies must be accompanied by robust safety, traceability and performance evaluations to ensure alignment with European regulatory frameworks and consumer expectations.

Real progress will require multi-actor piloting and territorial demonstration hubs where farmers, cooperatives, food processors, technology developers, researchers and regulators can test cascading pathways, validate safety and traceability protocols, assess economic feasibility and co-design governance and safety models. Strengthening these innovation ecosystems is key to unlocking the full potential of circularity across European protein value chains.

Potential Actions:

- **Apply a use-priority hierarchy for protein-rich biomass.** This requires establishing clear guidelines that prioritise food > feed > non-nutritional uses, ensuring valorisation decisions are based on nutritional, economic and environmental value. Such a hierarchy will optimise resource allocation and reinforce sustainability across the bioeconomy.
- **Develop low-energy, low-emission biorefinery technologies.** This requires advancing processes to extract and fractionate proteins, fibres and co-products from leaves, side streams and agro-industrial residues. Deploying these technologies will reduce environmental impact, enhance resource efficiency and unlock new value streams for diversified protein sources.
- **Advance enzymatic, microbial and fermentation-based processes for side streams.** This requires converting diverse agro-industrial residues into safe, high-value ingredients, supported by integrated safety, nutritional and sustainability assessments. Such innovations will enable circularity, reduce waste and create new market opportunities for alternative protein inputs.
- **Establish multi-actor piloting and territorial demonstration hubs.** This requires creating collaborative spaces where farmers, processors, SMEs and technology developers can test cascading use models, validate traceability and safety frameworks and co-design viable business models. These hubs will accelerate innovation uptake and foster regional bioeconomy ecosystems

4.5. Cross-cutting perspective: reasoning at the scale of the whole value chain and feed-food interface

For clarity, this document presents the analysis according to the main nodes of the protein value chain (primary production, processing, distribution and retail, consumption and circularity). This separation facilitates the identification of specific research and innovation needs at each stage. However, it is important to recognise that **significant opportunities arise from complementarities between nodes** and that many challenges overlap across stages, for instance, those related to quality standardisation, supply stability, traceability and environmental and nutritional performance indicators. The sections should therefore be read as **interconnected and complementary,** acknowledging that effective transition strategies depend on coordination across actors and governance levels throughout the entire protein system.

Beyond the analysis by individual nodes, systemic reasoning at the level of the entire value chain and particularly at the intersection between feed and food uses, is essential to ensure coherent and efficient protein transitions in Europe:

- **Integrate crop, processing and nutritional quality in R&I frameworks.** Strengthen interdisciplinary research linking plant breeding, agronomy, food science, nutrition and human health to jointly optimise protein yield, functional and nutritional quality and safety across feed and food applications. Integrate agroecological principles, including crop diversity, soil health and ecosystem service enhancement, into breeding and agronomic design. Develop multi-trait breeding tools and predictive quality markers enabling efficient allocation of raw materials between uses and reducing post-harvest losses. Include research on perennial and grass–clover systems to enhance nitrogen fixation and cycling efficiency.
- **Co-develop shared territorial infrastructures and innovation hubs.** Support regional pilot platforms and open-access facilities for storage, dehulling, fermentation or pressing that serve both feed and food outlets. Such infrastructures should act as experimental spaces for testing new technologies, logistics models and business arrangements, while contributing to regional autonomy and lower environmental footprints.
- **Establish harmonised sustainability metrics and data frameworks.** Advance methodological research to align environmental, nutritional and socio-economic indicators across value chains, covering protein quality, carbon and nitrogen balances, ecosystem services and circularity. Develop integrated databases and modelling tools to support transparent governance and evidence-based policy design.
- **Develop circular and cascading biorefinery pathways.** Promote research on safe, low-energy biorefinery processes to valorise co-products and residues into feed, fertilisers or biomaterials, while prioritising food use where feasible. Integrate techno-economic, environmental and social life-cycle assessment to guide sustainable cascading strategies within regional bioeconomy frameworks. Ensure alignment with food safety and novel food regulations, addressing allergenicity, traceability and process contaminants.
- **Advance multi-scale modelling, social innovation and participatory research.** Invest in data-driven models linking production, processing, market and consumption dynamics under varying climatic and socio-economic conditions. Strengthen Living Labs and Policy Labs connecting researchers, farmers, processors, consumers and policymakers to co-design innovations and governance solutions.
- **Design governance models for coordinated and fair value distribution.** Support applied research on multi-level governance mechanisms, including interbranch agreements, cooperative models and regional partnership, that enable coordination of flows, contracts and innovation investments. Comparative studies should identify policy and institutional levers that enhance trust, transparency and equitable value sharing across feed–food systems.

5. RECOMMENDATIONS

The transformation of Europe's protein system depends on research that fulfils a dual role: **deepening disciplinary knowledge** while **simultaneously developing the interfaces that connect disciplines.** Progress within each scientific field, whether in plant and microbial biology, food and feed technology, environmental modelling, or social and behavioural sciences, remains indispensable to address unresolved fundamental questions. Yet, these advances gain real transformative power when linked through shared frameworks, data and methodologies that bridge scales and sectors. Future European R&I should therefore **nurture both pillars: excellence within disciplines and integration across them**.

Figure 7. below, developed by the SCAR Protein TF, collect and summarise the potential actions grouped by the protein value chain stages structure followed in the analysis and further developed in Section 4:

Primary Production

- Invest in multi-criteria breeding programmes for yield stability, resilience, nutrition, and processability
- Develop predictive quality markers and high-throughput screening tools for raw material allocation
- Scale agroecological innovation through LLs, demo farms, and advisory networks with digital tools
- Strengthen EU observatories and interoperable data platforms for agronomic & market data integration

Feed Value Chain

- Deploy modular, low-cost processing technologies to valorise regional feedstocks and reduce imports
- Reduce anti-nutritional factors through combined breeding and processing strategies
- Create open-access nutritional databases and precision ration tools for diet optimisation
- Fund systematic multi-species feed trials to validate performance and health impacts
- Align feed innovation with One Health and climate-smart agriculture frameworks

Food Value Chain

- Advance predictive research on structure–function–nutrition relationships for better quality
- Invest in territorial processing hubs and pilot plants to scale protein innovations
- Harmonise EU labelling and regulatory frameworks with nutritional and environmental indicators
- Support culinary innovation and partnerships with chefs and food-service professionals
- Develop harmonised allergenicity assessment frameworks for emerging proteins

Circularity & End-of-Chain

- Apply a use-priority hierarchy (food > feed > non-nutritional uses) for biomass valorisation
- Develop low-energy, low-emission biorefinery technologies for cascading uses of co-products
- Advance enzymatic, microbial, and fermentation-based processes for side-stream valorisation
- Establish territorial demonstration hubs to test cascading pathways and governance models
- Integrate multi-criteria sustainability assessments into funding and regulatory frameworks

Cross-Cutting Priorities

- Create interoperable EU data infrastructures linking agronomic, processing & environmental datasets
- Standardise sustainability indicators across feed and food chains for transparent monitoring
- Design multi-level governance models to ensure fair value distribution and reduce transaction costs
- Embed protein diversification targets in CAP, rural development, and climate strategies
- Establish policy labs and living labs to co-design regulatory reforms and institutional arrangements

Figure 7. Summary of the potential actions suggested for R&I for alternative protein sources towards strategic autonomy and sustainability in EU protein production along the protein value chain

6. CONCLUSIONS AND PERSPECTIVES

This report reflects the collective analysis and expertise of the SCAR Protein TF. It draws on the expertise and time that members could allocate to this exercise and therefore inevitably bears the limitations associated with the scope of expertise represented, the time available for analysis and the broader uncertainties of an emerging interdisciplinary field.

A key point of convergence was the recognition that **transformative change still depends on fundamental understanding.** Despite strong momentum toward applied and technological innovation, **critical knowledge gaps persist at multiple points along the protein value chains.** The link between **protein molecular structure, techno-functional behavior and nutritional outcomes** is only one example among many where the underlying mechanisms remain poorly characterised. Without such fundamental understanding, scaling alternative protein systems risks generating technically viable yet nutritionally or environmentally suboptimal products, thus falling short of sustainability objectives. **Fundamental research should not be overlooked in the pursuit of short-term innovation and impact. Strengthening the scientific foundations of the protein transition, from molecular to system level, requires dedicated research spaces within future European R&I frameworks, alongside applied and demonstration actions.** To sustain transformative innovation, FP10 should strengthen the **continuity between fundamental and applied research**. Dedicated mechanisms, to be further elaborated, bridging Excellent Science and Thematic Clusters would help ensure that long-term, curiosity-driven knowledge is not lost in the shift toward short-term impact.

Conversely, some of the aspects addressed in this report remain subject to debate within the scientific and stakeholder communities. These include:

- **The long-term safety and health implications of novel foods and feeds,** which are still insufficiently characterised, for example with regards to products derived from side streams and residual biomass, where contaminant transfer (e.g. heavy metals, mycotoxins) and cumulative exposure may occur, or concerning the effects of (ultra)processing on overall sustainable and nutritional outcomes;
- **The regulatory landscape**, notably the frameworks for Novel Food and New Genomic Techniques, which remains highly sensitive and debated, reflecting diverging interests and interpretations among Member States, industry and civil society actors; and
- **The scalability and economic viability of certain alternative protein technologies** (e.g. insects, microbial fermentation), for which techno-economic assessments often rely on optimistic or non-transparent assumptions.

Also, several relevant aspects were only briefly addressed in this report, not because of limited importance but due to constraints in time and the specific expertise available within the TF. They are outlined below, ranging from topics that were partially developed to those only marginally addressed or absent:

- The need for **integrated, multi-criteria sustainability assessments** that combine environmental, nutritional, social and economic dimensions beyond conventional LCA approaches,
- The **socio-economic and institutional dimensions** of protein diversification, including mechanisms of contracting, coordination and value sharing across actors, as well as the interplay between **short and long supply chains**,
- The **potential of perennial legumes** to enhance nitrogen and carbon cycling,
- The **quality and governance of data**, as the reliability and interoperability of participatory research may lead to heterogeneous datasets which challenge **model-based scenario building and policy monitoring**,
- The international R&I dimension, beyond EU, including global sustainability challenges.

The report also reflects a **science-oriented perspective**, grounded primarily in peer-reviewed literature. Stakeholder and policy viewpoints were incorporated mainly through **grey literature (e.g. policy briefs)**. **The SCAR Protein TF recommends using this report as a basis for structured dialogue with experts and stakeholders from the different domains, it addresses, in order to refine priorities and potentially guide future R&I agenda.**

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